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Report of the Workshop on Ocean Climate of the NW Atlantic During the 1960s and 1970s and Consequences for Gadoid Populations

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1 Introduction and overview

1.1 Participants

A complete participant list, including communication addresses, is provided in Appendix 1. The workshop was convened by F. Werner (USA), S. Murawski (USA) and K. Brander (ICES/GLOBEC Coordinator).

1.2 Terms of reference

(C.Res.1997/2:6):

The Third ICES/GLOBEC Backward-Facing Workshop [WKBFAF] will:

- a) analyse the 1960s and the 1970s ocean climate in the Georges Bank, Scotian Shelf and Gulf of Maine and
- b) determine the conditions that may have contributed to the formation of outstanding gadoid year-classes during the 1960s and 1970s (e.g., 1966, 1971 and 1975 for cod; 1963, 1975 and 1978 for haddock on Georges Bank) including:
 - i differences in 3-D circulation fields of “cold” and “warm” years
 - ii effect of temperature differences on the distribution of predators
 - iii effect of temperature on larval growth rates
 - iv temporal and spatial distribution and abundance of eggs, larvae, juveniles and spawners.
- c) compare the processes which appear to govern interannual variability in gadoid recruitment on Georges Bank and in other areas of the North Atlantic.

WKBFAF will report to the Oceanography Committee at the 1998 Annual Science Conference.

1.3 Acknowledgments

The Workshop participants extend their appreciation and thanks to the staff of the Woods Hole Laboratory, National Marine Fisheries Service, and especially Ms. Joanne McDonald for logistical assistance. The Woods Hole Oceanographic Institute and National Marine Fisheries Service kindly provided meeting space, and their support is greatly appreciated.

1.4 Overview and background

A key component of the ICES/GLOBEC Cod and Climate Programme (ICES 1993) has been the facilitation of retrospective analyses of physical

oceanographic and other climate-related factors associated with observed changes in important fishery resource species. Previous “backward-facing” workshops have considered case studies of cod in the Northeast Arctic and tilefish in the Northwest Atlantic (ICES 1995; 1996), and synthesized available information in new and informative ways (e.g., Marsh *et al.*, 1999).

The objectives of the third backward-facing workshop relate specifically to gadoid stocks in the Georges Bank, Scotian Shelf and Gulf of Maine regions of the Northwest Atlantic (Figure 1.3.1). The long history of fishery-independent resource and physical oceanographic data, combined with the fisheries and oceanographic expertise and knowledge base developed in the NW Atlantic (through research programs like FEP, OPEN, GLOBEC, COP, MARMAP and others) make these natural targets of the BF-III workshop.

The historical record of fisheries for cod and haddock in the Georges Bank-Scotian Shelf region dates back over 400 years (Boreman *et al.*, 1997). Complete accounts of landings production by fishery stock date to the 1890s for the United States, and to the 1940s for Canada (Figures 1.3.2–1.3.4). Total landings production of the two species have varied widely over time, and particularly since the 1960s. A series of fishery, political and environmental events occurring in the region were responsible for these catch fluctuations (Parsons 1993; Boreman *et al.*, 1997), and disentangling the relative influences of these factors is of great significance to contemporary fishery management in both countries.

Beginning with the precipitous drop in landings of Georges Bank haddock in the late 1920s, there has been intensive investigation of the stock structure, population dynamics and effects of environmental and fishery influences on these species (Herrington 1944; Hennemuth *et al.*, 1964; Clark *et al.*, 1982; Serchuk and Wigley 1992; Frank *et al.*, 1994). The relationship among stock components of haddock and cod in the Scotian Shelf, Georges Bank and Gulf of Maine has been, and continues to be, the subject of investigation (Clark and Vladykov 1960; Wise 1963; Zwanenburg *et al.*, 1992; Purcell *et al.*, 1996). Early work on stock structure, employing a variety of methods, concluded that, for the purposes of management, separate stocks were:

Atlantic Cod-

- Eastern Scotian Shelf (NAFO Divisions 4VsW);
- Western Scotian Shelf (Browns Bank; NAFO Division 4X);
- Georges Bank (NAFO Division 5Z and Subarea 6);
- Gulf of Maine (NAFO Division 5Y).

Haddock-

- Eastern Scotian Shelf (NAFO Divisions 4TVW);
- Western Scotian Shelf (Browns Bank; NAFO Division 4X);
- Georges Bank (NAFO Division 5Z);
- Gulf of Maine (NAFO Division 5Y).

(See Figure 1.3.1 for NAFO Divisions in the region). Canada currently defines management units for the eastern portions of Georges Bank for cod and haddock (Hunt and Buzeta 1997; Gavaris and Van Eeckhaute 1997). It is beyond the scope of this meeting to explore stock structure in more detail, but previous research has documented a general correspondence in population attributes among the eastern and western portions of Georges Bank cod and haddock (Northeast Fisheries Science Center 1997). For the purposes of this workshop, the stock conventions given in the above bullets are used.

The Terms of Reference for this workshop specifically deal with the periods of the 1960s and 1970s when recruitment varied considerably within some of these stocks, and there were obvious cold and warm periods in the physical environment. Sections of this report describe evidence related to ocean climate variability during this and subsequent times, as well as production at various trophic levels and survival of cod and haddock eggs and larvae. There are two underlying questions which need to be addressed in dealing with the Terms of Reference:

(1) How are these stocks interrelated?

The question of the interrelationship of stocks in this region is important for two reasons. First, if there is significant movement of eggs, larvae or adults among the stock areas, then variations in recruitment may be partially explained by these exchanges, with obvious implications for fishery management. Second, depending on the spatial and temporal scales of coherence in related stocks (both inter- and intra-species), variations in stock size and yields among stocks may be coherent.

Landings data for the various species/stocks (over the period 1893–1996) show differing levels of coherence, with the strengths of correlations (r) varying from -0.38 to 0.83 (Figure 1.3.5 and Table 1.3.1). The highest pair-wise correlations are for Georges Bank and Browns Bank cod, Georges Bank and Eastern Scotian Shelf haddock, Georges Bank and Browns Bank haddock, and Eastern Scotian Shelf cod and haddock. These correlations are potentially confounded in recent years by the effects of fishery management, but the effects of intensive fisheries since the 1960s have been important to landings patterns and stock sizes in all of these fisheries (Sinclair and Murawski 1997).

Patterns of coherence in recruitment to these stocks has been investigated in a number of studies (Koslow 1984; Koslow *et al.*, 1987; Thompson and Page 1989; Cohen

and Mountain 1991; Sinclair 1996; Myers and Fogarty, Section 3.3). The detection of patterns of coherence in these data is confounded by the relatively short lengths of the time series, and the fact that correlations from such data may be artifacts (Thompson and Page 1989; Cohen and Mountain 1991; Sinclair 1996). Appropriate transformations for these data include first-differencing and detrending. Examination of empirical correlations in recruitment strength and recruitment survival (\log [recruitment/spawning stock biomass]) among stocks provides important data for investigating various hypotheses of factors influencing these population attributes (Myers *et al.*, 1990, Sinclair 1996).

Compilations of the time series of recruitment, spawning stock biomass, R/SSB and $\log(R/SSB)$ for cod and haddock stocks in the region are given in Tables 1.3.2–1.3.3, based on most recent virtual population analyses (Fanning *et al.*, 1996; Clark 1997; Hurley *et al.*, 1997; Northeast Fisheries Science Center 1997; Frank *et al.*, 1997). No virtual population analysis has been conducted for Gulf of Maine haddock, and the VPA time series for Georges Bank and Gulf of Maine cod are relatively short (and in the case of the Gulf of Maine, does not include any of the 1960s or 1970s). Accordingly, relative recruitment and SSB indices (catch per bottom trawl survey tow, 1963–1996) for Georges Bank and Gulf of Maine cod are presented in Table 1.3.4.

All pair-wise correlations between \log (recruitment) were computed for each of the 7 VPA stocks (Figure 1.3.6; Table 1.3.5); the largest of which were for stocks which also exhibited relatively strong correlations in landings (Table 1.3.1). The highest correlations in $\log(R)$ were between Gulf of Maine and Browns Bank cod, Georges Bank and Browns Bank cod, Georges Bank and Gulf of Maine cod, Browns Bank and Eastern Scotian Shelf haddock, and Georges Bank and Browns Bank haddock.

Recruitment survival ($\log[R/SSB]$) was most strongly correlated between Gulf of Maine and Browns Bank cod, Eastern Scotian Shelf cod and haddock, Georges Bank and Browns Bank haddock, and Georges Bank and Browns Bank cod (Figure 1.3.7; Table 1.3.6). These correlations are clearly highest among the adjacent stocks (or in the case of the Eastern Scotian Shelf, between species occupying the same area).

The coherence in patterns of recruitment survival among some of these adjacent stocks begs the question of regional-scale abiotic and biotic factors affecting survivorship, and these factors are considered below and in detail in Sections 2 and 3 of this report.

(2) Do physical factors significantly influence interannual variability in survival of various life stages?

Predicting the effects of climate change on fish stocks, such as gadoid populations in the NW Atlantic, requires establishing an environmental link to important population processes (Brander 1996). Knowledge of the

effects of environmental variation on recruitment survival is important for making medium-term fishery forecasts (those from 3 to ten years ahead), particularly if recruitment variation due to physical factors is autocorrelated (e.g., resulting in periods “good” and “poor” survival). Short-term forecasts (one to two years ahead) for the groundfish stocks considered here are not dependent on environmental information since extensive bottom trawl surveys index recruitment strength several times before year classes recruit to the fisheries (Figure 1.3.8).

Considerable research has been published on these stocks relating landings, recruitment and recruitment survival to variations in environmental conditions and SSB (Walford 1938; Herrington 1944; Chase 1955; Sutcliffe *et al.*, 1977; Drinkwater 1987; Overholtz *et al.*, 1986; Serchuk *et al.*, 1994; Frank *et al.*, 1994; Sinclair 1996; Sinclair and Murawski 1997).

Herrington (1944) proposed, based upon relative indices of stock and recruitment for Georges Bank haddock (1914 to 1940), that at high stock sizes, the expanding range of adults resulted in food competition with juveniles, and reduced juvenile survival (i.e., intra-specific competition among life stages). Grosslein (1966) discounted Herrington’s pre-1931 population size index data as potentially biased, thereby rendering the conclusion of interspecific competition and lower survival at high stock sizes null. More contemporary work on stock-recruitment relationships has shown that, on average, there is a higher probability of a stock producing moderate to good year classes if SSB is relatively high, rather than low, and vice-versa. Stock-recruitment relationships can be fitted for most populations considered here (Overholtz *et al.*, 1986; Myers *et al.*, 1990; NEFSC 1997), although they tend to be ‘noisy’. Thus, even though recruitment survival may fluctuate due to environmental variability, larger SSBs will, on average, result in higher average recruitment than if SSBs are low. This finding implies that the potential environmental signals influencing recruitment will appear as residuals from the stock recruitment relationship, or as deviations from the median recruit per unit spawning biomass (i.e., assuming a linear S-R relationship).

Walford (1938) examined the distribution and abundance of cod and haddock eggs in 1931 and 1932, concluding that in one year (1932) there was significant advection of eggs off the northern and southern portions of Georges Bank, presumably into less favourable conditions. Walford concluded that there was an important connection between recruitment success and water mass movements. He further noted that there was considerable spatial variation in source of eggs between years (1931 had one large group of eggs spawned on the Northeast Peak of the Bank, while in 1932 there were two bodies of eggs, in the Northeast Peak and Great South Channel areas). Walford also documented drift of haddock larvae to the Middle Atlantic Bight, the significance of which was subsequently established some 56 years later in 1987 by Polacheck *et al.* (1992). In retrospect, while

Walford’s work showed that there were significant annual differences in the spatial extent, timing and role of physical variation in the early life history of cod and haddock, ironically, the haddock cohorts spawned in the two years of his study (1931 and 1932) were approximately the same size (50 million fish at age 1). By historical standards, these are modest year classes, but would be considered large cohorts now (Table 1.3.3). The significance of Walford’s work was to establish that relatively similar recruiting haddock year class sizes do not necessarily originate from the same environmental scenarios.

Chase (1955) argued that offshore winds during the egg and early larval period (February to May) could result in advection of haddock off Georges Bank, and proposed a “damage” index based on the number of days during this period that the atmospheric pressure difference between Nantucket, MA, and Yarmouth NS was 5 mb, or 10 mb. Chase concluded from empirical evidence that pressure differences of 5mb corresponded to a surface wind speed of ca. 20 MPH. Correlating this index with relative recruitment indices for the period 1928–1951 resulted in a linear relationship, with several notable outliers. The relationship was improved with the addition of water temperature data, eventually explaining about 60% of the variation in recruitment. With the addition of subsequent years of data, however, this relationship resulted in poorer predictions.

Research conducted on the effects of outflow from the St. Lawrence on fish catches in the Gulf of Maine showed early promise (Sutcliffe *et al.*, 1977), but again performed more poorly when additional information was added, and time-series methods were applied to the data (Drinkwater 1987; Frank *et al.*, 1994). Inspection of recruitment variability in relation to a variety of environmental variables for stocks in this region showed either low correlations or no relationship among variables (Sinclair and Murawski 1997).

Both the United States and Canada have mounted significant field programs to evaluate mechanisms relating recruitment survival to physical variation. In the 1970s and 1980s, the MARMAP and SSIP programs collected substantial ichthyoplankton and associated data, which formed the basis of much of our knowledge of processes affecting eggs and larvae, prior to the intensive field programs conducted under GLOBEC and OPEN (Morse 1994). A potentially crucial piece of information from these data is the apparent correlation between the relative abundance of 3–5 mm Georges Bank cod larvae, and subsequent age 1 recruitment (Morse 1994). If recruitment strength is determined by the early larval stage, then the focus on factors responsible for variations in year class survival can be narrowed considerably (e.g., to factors influencing egg survival and success of first feeding of larvae, including the abundance and distribution of appropriate zooplankton prey). Relationships among egg and larval survival and resulting year class size are treated in more detail in Section 3 of this report.

Retrospective analyses of the MARMAP data in combination with sophisticated 3-D numerical circulation models have provided important new clues regarding the relative influences of advective losses for the 1982 (poor) and 1985 (very good) year classes of cod on Georges Bank (Lough *et al.*, 1994). Circulation models, tuned to historic meteorological data and validated by field sampling of the biota data can potentially shed new light on physical processes responsible for the observed fluctuations in fish populations (Werner *et al.*, 1993). New research results from the GLOBEC program and other contemporary studies are beginning to yield important insights into processes responsible for variations in recruitment survival of gadoids. It is the purpose of this workshop to

bring together new tools in combination with old data (some of which was not heretofore available) to seek a consistent interpretation of events responsible for recruitment variability as demonstrated in the 1960s and 1970s. Specifically, Sections 2, 3,4 and 5 of this report:

- inventory and interpret physical and biological data available to explain factors responsible for gadoid recruitment variation in the 1960s and 1970s;
- generate and suggest tests of hypotheses regarding recruitment mechanisms;
- recommend additional data analyses and other studies, as necessary, to lend greater insights into the interpretation of events in the target time period.

Table 1.3.1. Correlation coefficients (r) between annual landings (MT) of 8 cod and haddock stocks in the Scotian Shelf, Gulf of Maine and Georges Bank region, 1893–1996.

Pearson correlation matrix (values ± 0.6 are bolded)

	COD-5Z	COD-5Y	COD-4X	COD-4VSW	HAD-5Z	HAD-5Y	HAD-4X	HAD-4VW
COD-5Z	1.00							
COD-5Y	0.62	1.00						
COD-4X	0.83	0.36	1.00					
COD-4VSW	0.44	-0.20	0.48	1.00				
HAD-5Z	-0.08	-0.38	-0.04	0.48	1.00			
HAD-5Y	-0.03	-0.31	0.16	0.34	0.49	1.00		
HAD-4X	0.42	-0.14	0.63	0.56	0.65	0.63	1.00	
HAD-4VW	-0.01	-0.52	0.02	0.65	0.82	0.57	0.44	1.00

Pairwise frequency table (Numbers of years where landings data are compared between stocks)

	COD-5Z	COD-5Y	COD-4X	COD-4VSW	HAD-5Z	HAD-5Y	HAD-4X	HAD-4VW
COD-5Z	104							
COD-5Y	104	104						
COD-4X	66	66	66					
COD-4VSW	43	43	43	43				
HAD-5Z	104	104	66	43	104			
HAD-5Y	66	66	66	43	66	66		
HAD-4X	49	49	49	43	49	49	49	
HAD-4VW	39	39	39	39	39	39	39	39

Table 1.3.2. Spawning stock biomass (SSB), recruitment (R) and recruitment survival for four cod stocks in the Scotian Shelf-Georges Bank region. Data are from virtual population analyses (SSB in kmt, recruitment in millions).

Year	5Z-Cod				5Y-Cod				4X-Cod				4VW-Cod			
	SSB	R	R/SSB	logR/SSB	SSB	R	R/SSB	logR/SSB	SSB	R	R/SSB	logR/SSB	SSB	R	R/SSB	logR/SSB
1948									48.96	25.20	0.51	-0.664				
1949									55.25	12.45	0.23	-1.490				
1950									63.48	15.92	0.25	-1.383				
1951									60.51	8.93	0.15	-1.913				
1952									56.82	18.61	0.33	-1.116				
1953									60.47	9.67	0.16	-1.833				
1954									59.89	14.40	0.24	-1.426				
1955									58.65	16.71	0.28	-1.256				
1956									56.06	19.43	0.35	-1.060				
1957									43.48	16.04	0.37	-0.997				
1958									43.15	23.77	0.55	-0.596	122.56	95.80	0.78	-0.246
1959									45.32	29.60	0.65	-0.426	124.14	108.28	0.87	-0.137
1960									43.24	18.88	0.44	-0.829	119.64	93.51	0.78	-0.246
1961									60.37	22.95	0.38	-0.967	146.10	141.14	0.97	-0.035
1962									63.91	33.58	0.53	-0.643	150.74	158.57	1.05	0.051
1963									62.05	43.22	0.70	-0.362	152.39	152.77	1.00	0.002
1964									71.32	20.64	0.29	-1.240	152.20	145.33	0.95	-0.046
1965									76.78	16.57	0.22	-1.533	133.50	153.35	1.15	0.139
1966									89.43	16.18	0.18	-1.710	105.18	120.75	1.15	0.138
1967									84.05	14.40	0.17	-1.764	103.65	74.19	0.72	-0.334
1968									75.62	20.80	0.28	-1.291	112.63	88.47	0.79	-0.241
1969									66.86	19.60	0.29	-1.227	93.89	93.32	0.99	-0.006
1970									60.70	15.20	0.25	-1.385	111.32	93.50	0.84	-0.174
1971									58.05	20.70	0.36	-1.031	115.42	76.96	0.67	-0.405
1972									52.92	24.27	0.46	-0.779	96.05	73.14	0.76	-0.272
1973									55.03	20.45	0.37	-0.990	77.09	89.07	1.16	0.144
1974									53.32	25.43	0.48	-0.741	51.51	106.98	2.08	0.731
1975									55.00	24.65	0.45	-0.802	50.43	90.88	1.80	0.589
1976									64.39	17.21	0.27	-1.319	36.41	91.75	2.52	0.924
1977									69.56	32.50	0.47	-0.761	43.69	135.30	3.10	1.130
1978	80.63	23.51	0.29	-1.232					75.78	29.57	0.39	-0.941	75.36	127.22	1.69	0.524
1979	89.50	20.11	0.22	-1.493					73.36	23.05	0.31	-1.158	110.03	156.65	1.42	0.353
1980	92.77	41.39	0.45	-0.807					80.78	25.93	0.32	-1.136	118.06	194.41	1.65	0.499
1981	86.59	17.47	0.20	-1.601					83.68	14.16	0.17	-1.777	125.58	134.72	1.07	0.070
1982	89.81	9.62	0.11	-2.234	24.64	5.53	0.22	-1.493	77.91	13.91	0.18	-1.723	144.83	156.09	1.08	0.075
1983	78.40	27.40	0.35	-1.051	21.05	7.75	0.37	-1.000	72.82	17.58	0.24	-1.421	152.78	99.05	0.65	-0.433
1984	67.29	8.68	0.13	-2.048	19.90	4.91	0.25	-1.399	64.04	9.97	0.16	-1.860	179.30	109.30	0.61	-0.495
1985	55.49	42.81	0.77	-0.259	17.64	7.41	0.42	-0.867	56.45	27.50	0.49	-0.719	216.59	153.89	0.71	-0.342
1986	57.46	16.39	0.29	-1.254	18.52	9.95	0.54	-0.621	51.73	18.68	0.36	-1.019	207.78	191.20	0.92	-0.083
1987	68.39	23.49	0.34	-1.069	21.88	21.65	0.99	-0.011	44.69	27.58	0.62	-0.483	171.02	166.96	0.98	-0.024
1988	73.81	15.80	0.21	-1.542	37.43	3.38	0.09	-2.406	51.16	9.18	0.18	-1.718	123.10	69.53	0.56	-0.571
1989	72.26	9.36	0.13	-2.044	31.32	3.39	0.11	-2.223	51.86	14.17	0.27	-1.297	90.43	52.59	0.58	-0.542
1990	68.55	19.18	0.28	-1.274	25.56	5.88	0.23	-1.469	60.88	16.18	0.27	-1.325	64.54	55.35	0.86	-0.154
1991	53.14	7.96	0.15	-1.899	21.03	5.34	0.25	-1.371	52.47	12.26	0.23	-1.454	51.07	38.24	0.75	-0.289
1992	40.81	10.84	0.27	-1.325	16.65	8.25	0.50	-0.702	44.29	27.53	0.62	-0.476	40.03	47.15	1.18	0.164
1993	32.59	10.12	0.31	-1.170	18.55	3.44	0.19	-1.686	31.99	10.46	0.33	-1.118	13.47	64.55	4.79	1.567
1994	25.14	3.52	0.14	-1.965	15.91	1.64	0.10	-2.272	30.47	7.47	0.25	-1.406	12.65	65.68	5.19	1.647
1995	27.77	6.25	0.22	-1.492	12.32	1.07	0.09	-2.446	41.83	5.55	0.13	-2.020				
1996	34.19	6.46	0.19	-1.667	8.90	0.52	0.06	-2.834								
1997	35.92	0.42			5.26											

Table 1.3.3. Time series of spawning stock biomass (SSB), recruitment (R) and recruitment survival for three haddock stocks in the Scotian Shelf-Georges Bank region. Data are from virtual population analyses (SSB in kmt, recruitment in millions).

Year	5Z-Had				4X-Had				4VW-Had			
	SSB	R	R/SSB	logR/SSB	SSB	R	R/SSB	logR/SSB	SSB	R	R/SSB	logR/SSB
1931	107.65	46.45	0.4315	-0.8405								
1932	103.80	52.50	0.5058	-0.6817								
1933	87.81	61.34	0.6986	-0.3587								
1934	78.02	59.11	0.7576	-0.2776								
1935	83.88	58.62	0.6989	-0.3583								
1936	85.57	106.41	1.2435	0.2180								
1937	81.82	79.55	0.9723	-0.0281								
1938	93.24	60.38	0.6476	-0.4345								
1939	110.45	112.28	1.0166	0.0164								
1940	106.87	115.34	1.0793	0.0763								
1941	115.70	62.09	0.5366	-0.6224								
1942	120.83	23.64	0.1956	-1.6314								
1943	121.61	66.79	0.5492	-0.5993								
1944	105.34	51.75	0.4913	-0.7108								
1945	101.40	94.70	0.9339	-0.0684								
1946	97.54	60.76	0.6229	-0.4733								
1947	92.92	34.66	0.3730	-0.9862								
1948	89.08	125.97	1.4141	0.3465					64.47	39.92	0.6191	-0.4795
1949	73.18	59.14	0.8081	-0.2130					61.00	72.50	1.1885	0.1727
1950	79.65	105.92	1.3298	0.2850					57.52	34.77	0.6046	-0.5032
1951	85.08	43.56	0.5120	-0.6695					53.66	26.58	0.4954	-0.7024
1952	89.13	134.23	1.5060	0.4095					66.57	122.47	1.8398	0.6096
1953	87.92	53.50	0.6085	-0.4967					64.88	42.93	0.6617	-0.4129
1954	100.34	93.28	0.9296	-0.0730					78.26	44.35	0.5667	-0.5680
1955	113.33	61.25	0.5405	-0.6153					60.79	64.37	1.0590	0.0573
1956	122.19	61.95	0.5070	-0.6792					50.68	80.08	1.5802	0.4575
1957	121.98	59.85	0.4907	-0.7120					76.24	70.01	0.9183	-0.0852
1958	118.45	131.96	1.1141	0.1080					66.99	29.73	0.4438	-0.8124
1959	127.01	124.99	0.9841	-0.0160					60.98	48.48	0.7950	-0.2294
1960	153.95	54.93	0.3568	-1.0306					51.27	33.46	0.6527	-0.4267
1961	195.74	39.49	0.2017	-1.6007					56.96	58.68	1.0302	0.0298
1962	199.53	190.71	0.9558	-0.0452	121.49	91.67	0.7545	-0.2817	59.08	84.52	1.4307	0.3582
1963	156.81	471.89	3.0093	1.1017	125.05	201.01	1.6075	0.4747	45.43	91.80	2.0208	0.7035
1964	128.56	33.15	0.2579	-1.3554	109.76	16.14	0.1471	-1.9170	41.30	91.52	2.2160	0.7957
1965	145.03	4.14	0.0285	-3.5562	113.05	10.07	0.0891	-2.4178	33.14	15.28	0.4612	-0.7739
1966	180.53	12.95	0.0717	-2.6348	176.45	17.38	0.0985	-2.3177	21.76	14.75	0.6780	-0.3886
1967	112.11	0.42	0.0037	-5.5870	141.47	8.06	0.0570	-2.8648	20.13	10.73	0.5332	-0.6289
1968	75.10	0.99	0.0132	-4.3289	111.58	14.46	0.1296	-2.0431	24.47	6.72	0.2746	-1.2926
1969	51.19	4.66	0.0910	-2.3965	85.67	25.34	0.2958	-1.2182	21.50	8.18	0.3805	-0.9664
1970	38.52	0.37	0.0096	-4.6454	58.64	6.09	0.1038	-2.2655	21.87	4.53	0.2071	-1.5744
1971	30.24	8.52	0.2817	-1.2667	50.17	47.14	0.9396	-0.0623	16.27	8.17	0.5024	-0.6884
1972	26.93	19.42	0.7211	-0.3269	48.75	44.06	0.9039	-0.1010	7.51	8.60	1.1463	0.1365
1973	12.28	10.55	0.8591	-0.1518	37.31	24.37	0.6533	-0.4257	5.87	4.75	0.8089	-0.2120
1974	21.83	7.66	0.3509	-1.0473	48.85	49.16	1.0063	0.0062	3.68	26.36	7.1678	1.9696
1975	18.39	103.33	5.6188	1.7261	63.79	54.10	0.8480	-0.1648	3.33	32.90	9.8716	2.2897
1976	22.08	13.82	0.6259	-0.4686	64.82	32.02	0.4940	-0.7052	4.12	48.88	11.8600	2.4732
1977	41.48	6.08	0.1466	-1.9202	75.16	42.90	0.5708	-0.5607	6.77	62.87	9.2892	2.2288
1978	68.95	84.01	1.2184	0.1976	98.35	33.86	0.3443	-1.0663	7.21	32.35	4.4861	1.5010
1979	67.82	10.15	0.1497	-1.8994	97.35	44.43	0.4564	-0.7845	14.51	49.42	3.4066	1.2257
1980	63.58	7.23	0.1137	-2.1741	102.12	51.97	0.5090	-0.6754	27.89	84.98	3.0469	1.1141
1981	55.74	2.49	0.0447	-3.1084	94.48	31.78	0.3364	-1.0894	40.10	77.45	1.9314	0.6583
1982	45.64	3.13	0.0686	-2.6798	91.14	38.01	0.4170	-0.8746	47.67	67.12	1.4081	0.3422
1983	35.36	17.31	0.4895	-0.7143	92.80	12.90	0.1390	-1.9730	46.18	39.86	0.8632	-0.1472
1984	25.48	1.77	0.0695	-2.6669	82.86	9.57	0.1155	-2.1584	54.56	18.05	0.3309	-1.1061
1985	19.98	14.86	0.7437	-0.2961	85.38	5.53	0.0647	-2.7374	64.80	8.43	0.1301	-2.0396
1986	20.08	2.20	0.1096	-2.2113	76.63	8.50	0.1110	-2.1984	66.56	5.29	0.0794	-2.5330
1987	18.66	16.98	0.9100	-0.0943	65.29	25.63	0.3925	-0.9351	65.59	21.86	0.3333	-1.0987
1988	17.84	1.11	0.0622	-2.7771	40.91	22.35	0.5464	-0.6045	65.33	44.04	0.6742	-0.3942
1989	18.41	2.78	0.1510	-1.8904	30.99	7.14	0.2304	-1.4679	57.54	7.01	0.1217	-2.1059
1990	20.78	2.56	0.1232	-2.0940	42.60	7.40	0.1737	-1.7505	46.69	2.62	0.0562	-2.8796
1991	18.95	10.03	0.5293	-0.6362	50.88	9.34	0.1836	-1.6952	34.02	2.77	0.0813	-2.5096
1992	14.31	17.66	1.2341	0.2103	39.88	24.52	0.6150	-0.4862	27.87	14.98	0.5374	-0.6210
1993	11.89	13.36	1.1236	0.1166	30.42	59.33	1.9503	0.6680	27.24	25.87	0.9496	-0.0517
1994	16.04	10.14	0.6322	-0.4586	30.75	74.88	2.4351	0.8900	20.41			
1995	27.55	8.91	0.3234	-1.1288	41.24	19.02	0.4613	-0.7738	15.56			
1996	33.51	13.77	0.4109	-0.8894	70.66				13.37			

Table 1.3.4. Time series of relative spawning stock biomass and recruitment for Georges Bank and Gulf of Maine cod, 1963–1996. Indices are spawning stock biomass per standard trawl tow (SSBi, kg), and age 1 numbers per tow (Ri).

Year	Cod - 5Z			Cod - 5Y		
	SSBi	Ri	log(R/SSB)	SSBi	Ri	log(R/SSB)
1963	17.30	0.64	-3.2970	17.60	0.09	-5.2539
1964	9.82	1.30	-2.0228	21.93	0.85	-3.2504
1965	10.63	1.69	-1.8372	11.23	0.20	-4.0082
1966	6.52	7.60	0.1527	12.18	0.13	-4.5477
1967	10.20	0.31	-3.4808	9.20	0.04	-5.5434
1968	7.47	0.34	-3.0809	19.19	0.06	-5.7846
1969	6.83	1.69	-1.3978	15.32	0.94	-2.7900
1970	10.79	0.60	-2.8861	15.72	0.18	-4.4809
1971	9.03	7.44	-0.1933	16.19	5.58	-1.0654
1972	18.80	1.75	-2.3748	12.13	0.33	-3.6104
1973	27.29	0.41	-4.2006	8.42	1.12	-2.0146
1974	6.80	0.99	-1.9229	8.84	0.15	-4.0966
1975	12.08	6.15	-0.6754	8.19	0.24	-3.5176
1976	14.58	0.24	-4.1193	6.46	0.02	-5.6823
1977	10.73	1.86	-1.7552	9.73	1.37	-1.9611
1978	20.49	1.62	-2.5381	12.19	0.37	-3.5003
1979	14.31	0.82	-2.8619	15.23	1.26	-2.4890
1980	5.82	3.53	-0.5014	12.96	0.62	-3.0415
1981	16.58	0.88	-2.9417	7.88	0.70	-2.4210
1982	5.20	0.65	-2.0841	13.30	1.66	-2.0809
1983	6.01	2.50	-0.8787	7.61	0.38	-2.9866
1984	8.82	0.22	-3.6911	8.15	0.38	-3.0709
1985	2.98	2.28	-0.2677	7.26	0.30	-3.1830
1986	3.90	0.41	-2.2429	4.35	0.60	-1.9827
1987	3.82	0.90	-1.4423	3.12	1.95	-0.4695
1988	5.16	2.74	-0.6337	5.31	0.42	-2.5467
1989	3.86	0.36	-2.3668	4.04	0.03	-4.9367
1990	6.37	0.42	-2.7311	4.90	0.14	-3.5412
1991	1.20	0.45	-0.9720	2.71	0.29	-2.2348
1992	2.47	0.97	-0.9347	2.22	0.20	-2.4170
1993	1.73	0.41	-1.4495	0.87	0.21	-1.4214
1994	2.78	0.25	-2.4289	2.35	0.07	-3.5137
1995	3.11	0.24	-2.5617	3.44	0.12	-3.3557
1996	0.95	0.24	-1.3926	2.20	0.30	-2.0025

Table 1.3.5. Correlation coefficients (r) between annual log (Recruitment) values of 7 cod and haddock stocks in the Scotian Shelf, Gulf of Maine and Georges Bank region, 1931–1996.

Pearson correlation matrix (values ± 0.6 are bolded)

	COD-5Z	COD-5Y	COD-4X	COD-4VW	HAD-5Z	HAD-4X	HAD-4VW
COD-5Z	1.00						
COD-5Y	0.69	1.00					
COD-4X	0.77	0.89	1.00				
COD-4VW	0.59	0.52	0.46	1.00			
HAD-5Z	0.15	-0.02	0.36	0.20	1.00		
HAD-4X	-0.17	-0.30	0.33	0.21	0.64	1.00	
HAD-4VW	0.27	-0.05	0.15	0.55	0.56	0.66	1.00

Pairwise frequency table (Numbers of years where log[Recruitment] data are compared between stocks)

	COD-5Z	COD-5Y	COD-4X	COD-4VW	HAD-5Z	HAD-4X	HAD-4VW
COD-5Z	20						
COD-5Y	15	15					
COD-4X	18	14	48				
COD-4VW	17	13	37	37			
HAD-5Z	19	15	48	37	66		
HAD-4X	18	14	34	33	34	34	
HAD-4VW	16	12	46	36	46	32	46

Table 1.3.6. Correlation coefficients (r) between annual log(R/SSB) values (an index of survival rate) of 7 cod and haddock stocks in the Scotian Shelf, Gulf of Maine and Georges Bank region, 1893–1996.

Pearson correlation matrix (values ± 0.6 are bolded)

	COD-5Z	COD-5Y	COD-4X	COD-4VW	HAD-5Z	HAD-4X	HAD-4VW
COD-5Z	1.00						
COD-5Y	0.49	1.00					
COD-4X	0.60	0.74	1.00				
COD-4VW	0.02	-0.20	0.12	1.00			
HAD-5Z	0.38	0.27	0.52	0.29	1.00		
HAD-4X	-0.24	-0.41	0.42	0.59	0.63	1.00	
HAD-4VW	0.03	-0.11	0.18	0.65	0.28	0.55	1.00

Pairwise frequency table (Numbers of years where log[R/SSB] data are compared between stocks)

	COD-5Z	COD-5Y	COD-4X	COD-4VW	HAD-5Z	HAD-4X	HAD-4VW
COD-5Z	19						
COD-5Y	15	15					
COD-4X	18	14	48				
COD-4VW	17	13	37	37			
HAD-5Z	19	15	48	37	66		
HAD-4X	18	14	34	33	34	34	
HAD-4VW	16	12	46	36	46	32	46

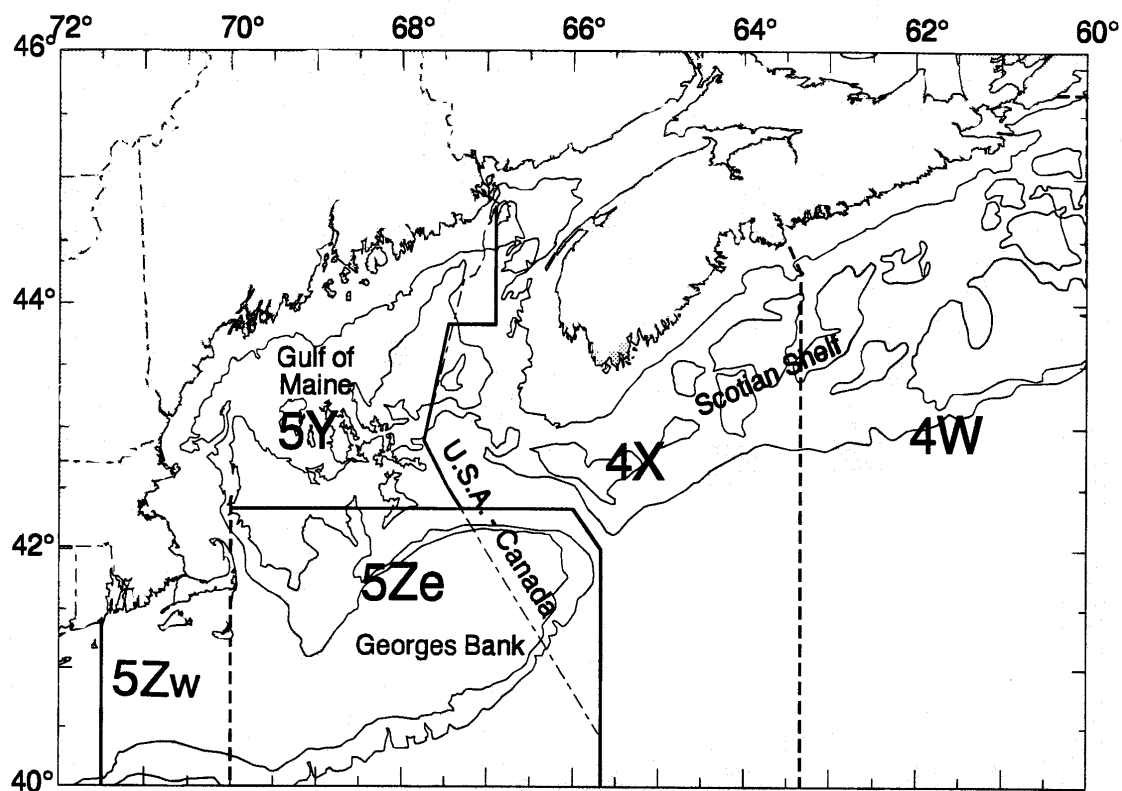


Figure 1.3.1. Geographic regions identified in the current report. Number/letter designations are NAFO subdivisions. The Eastern Scotian Shelf region E. of 60° is designated subdivision 4V.

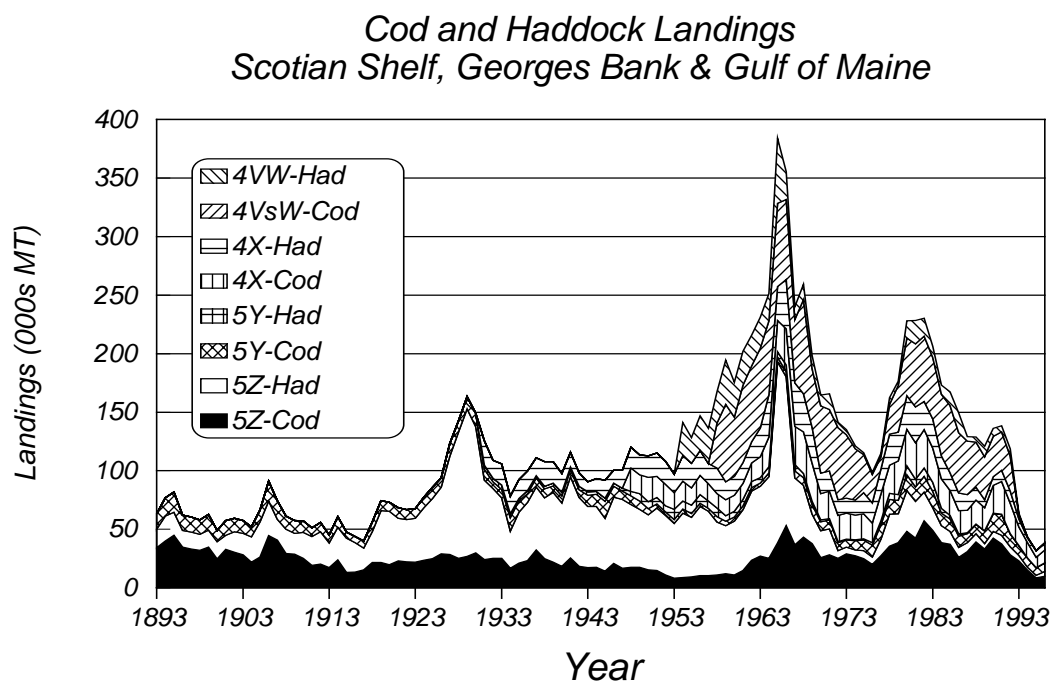


Figure 1.3.2. Landings (metric tons, thousands) of cod and haddock stocks (identified by NAFO subdivision) in the Georges Bank, Gulf of Maine, Browns Bank, and E. Scotian Shelf regions. Data for USA stocks date to 1893, Canadian data variously date to the 1940s.

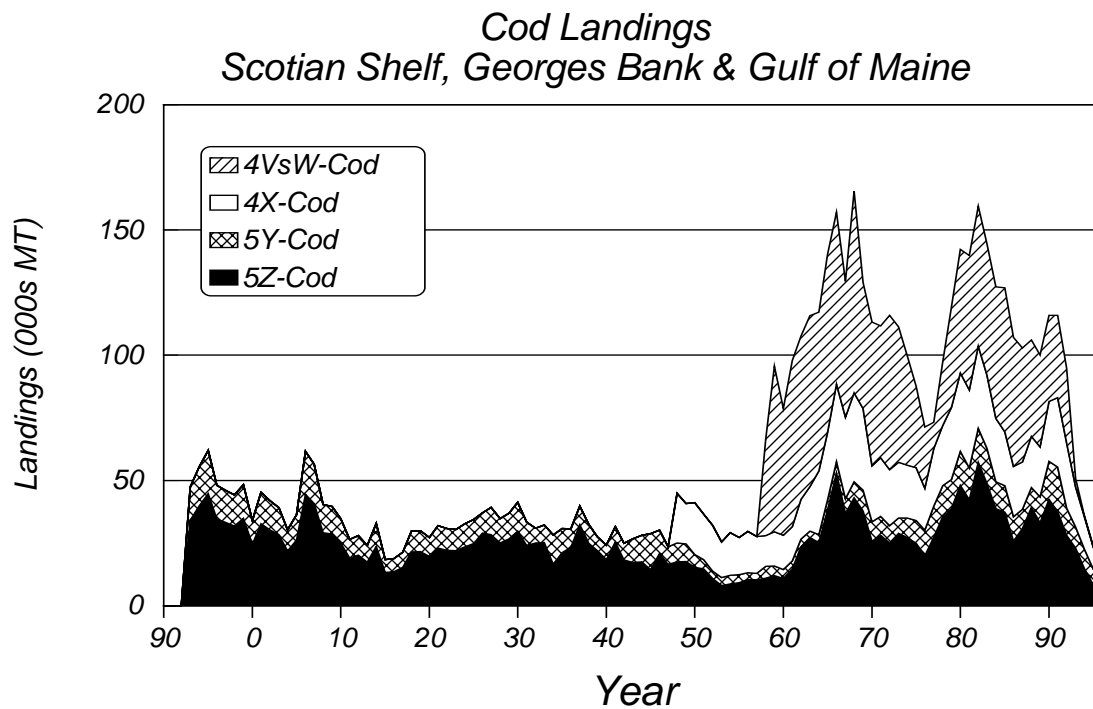


Figure 1.3.3. Landings (metric tons, thousands) of cod stocks (identified by NAFO subdivision) in the Georges Bank, Gulf of Maine, Browns Bank, and E. Scotian Shelf regions. Data for USA stocks date to 1893, Canadian data variously date to the 1940s.

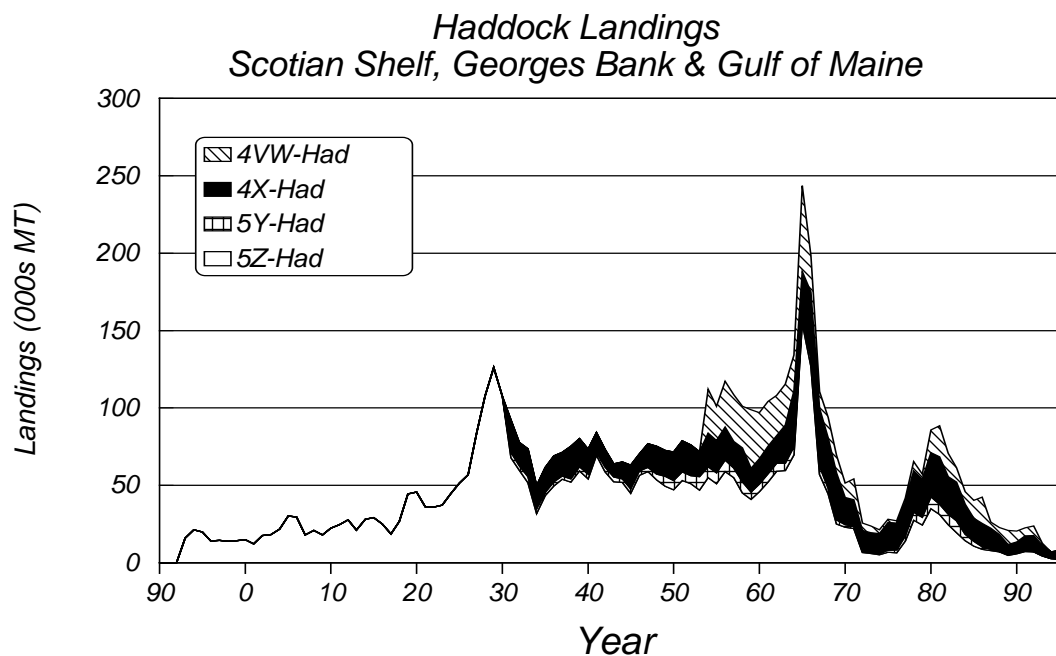


Figure 1.3.4. Landings (metric tons, thousands) of haddock stocks (identified by NAFO subdivision) in the Georges Bank, Gulf of Maine, Browns Bank, and E. Scotian Shelf regions. Data for USA stocks date to 1893, Canadian data variously date to the 1940s.

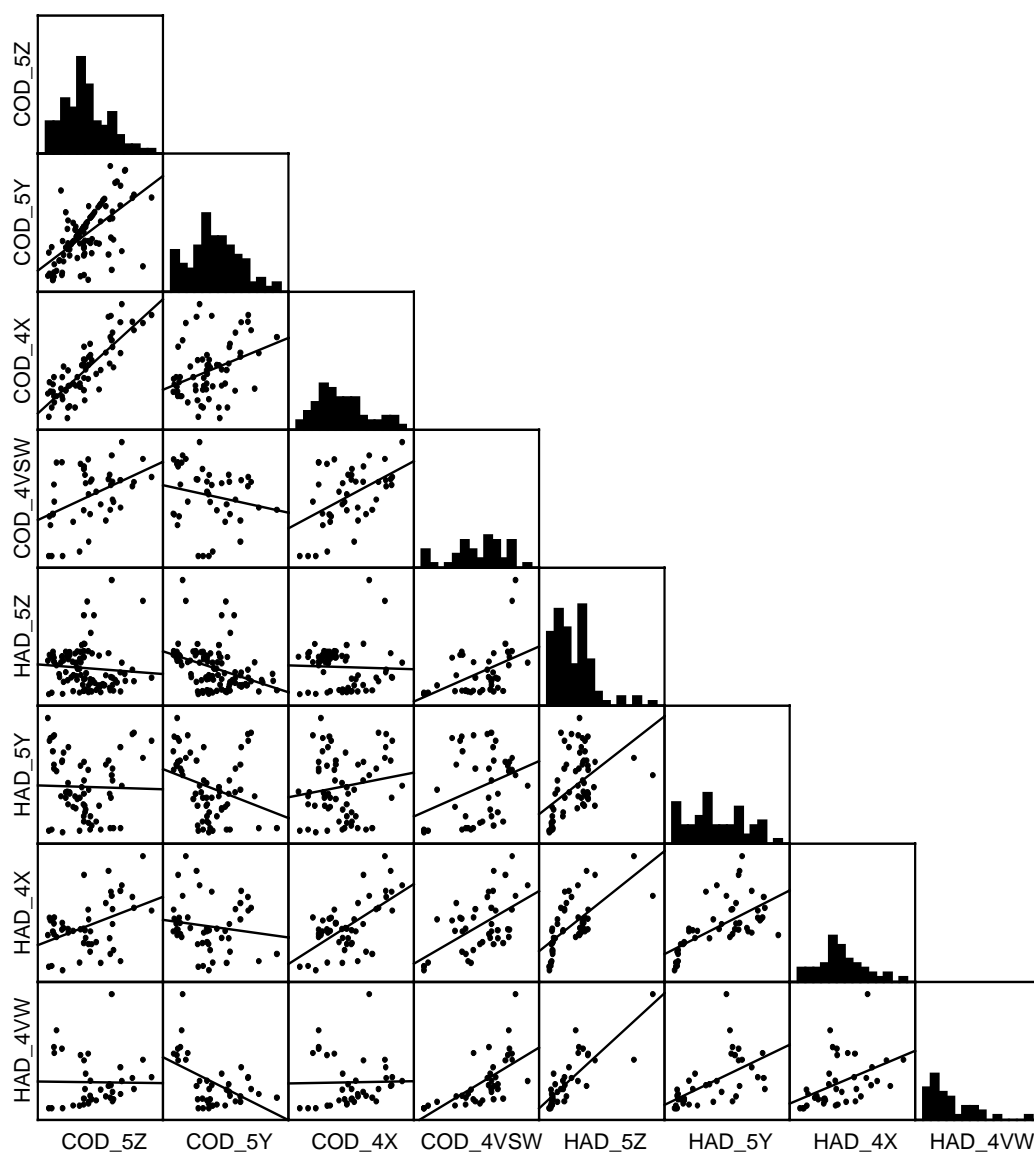


Figure 1.3.5. Pair-wise correlations between landings (metric tons, thousands) of cod and haddock stocks (8) in the Georges Bank (5Z), Gulf of Maine (5Y), Browns Bank (4x), and E. Scotian Shelf (4VW) areas. Data date as far back as possible (Figure 1.3.2).

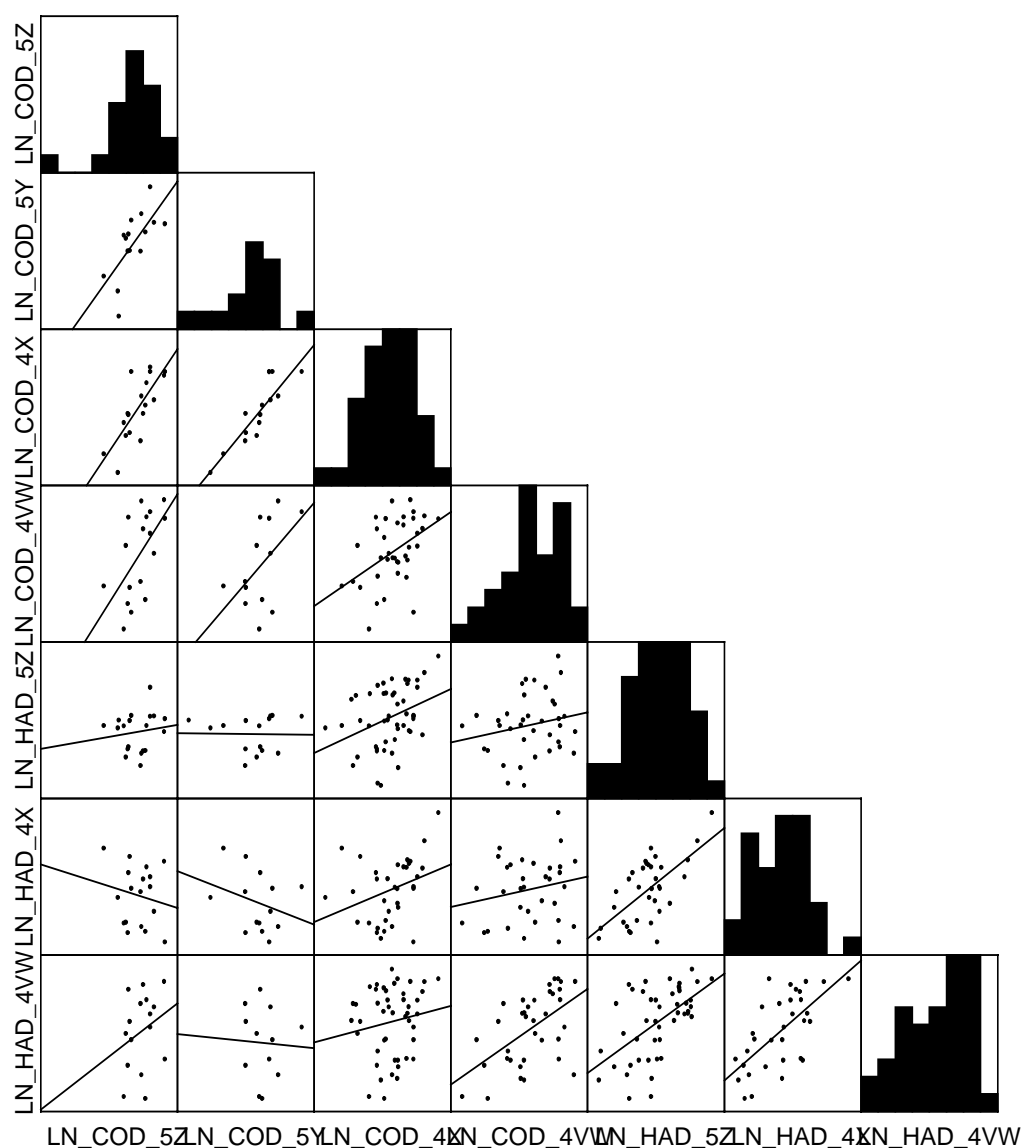


Figure 1.3.6. Pair-wise correlations between log(recruitment, millions of age 1 fish) of cod and haddock stocks (7) in the Georges Bank (5Z), Gulf of Maine (5Y), Browns Bank (4X), and E. Scotian Shelf (4VW) areas. Data are given only for stocks which are assessed with VPA.

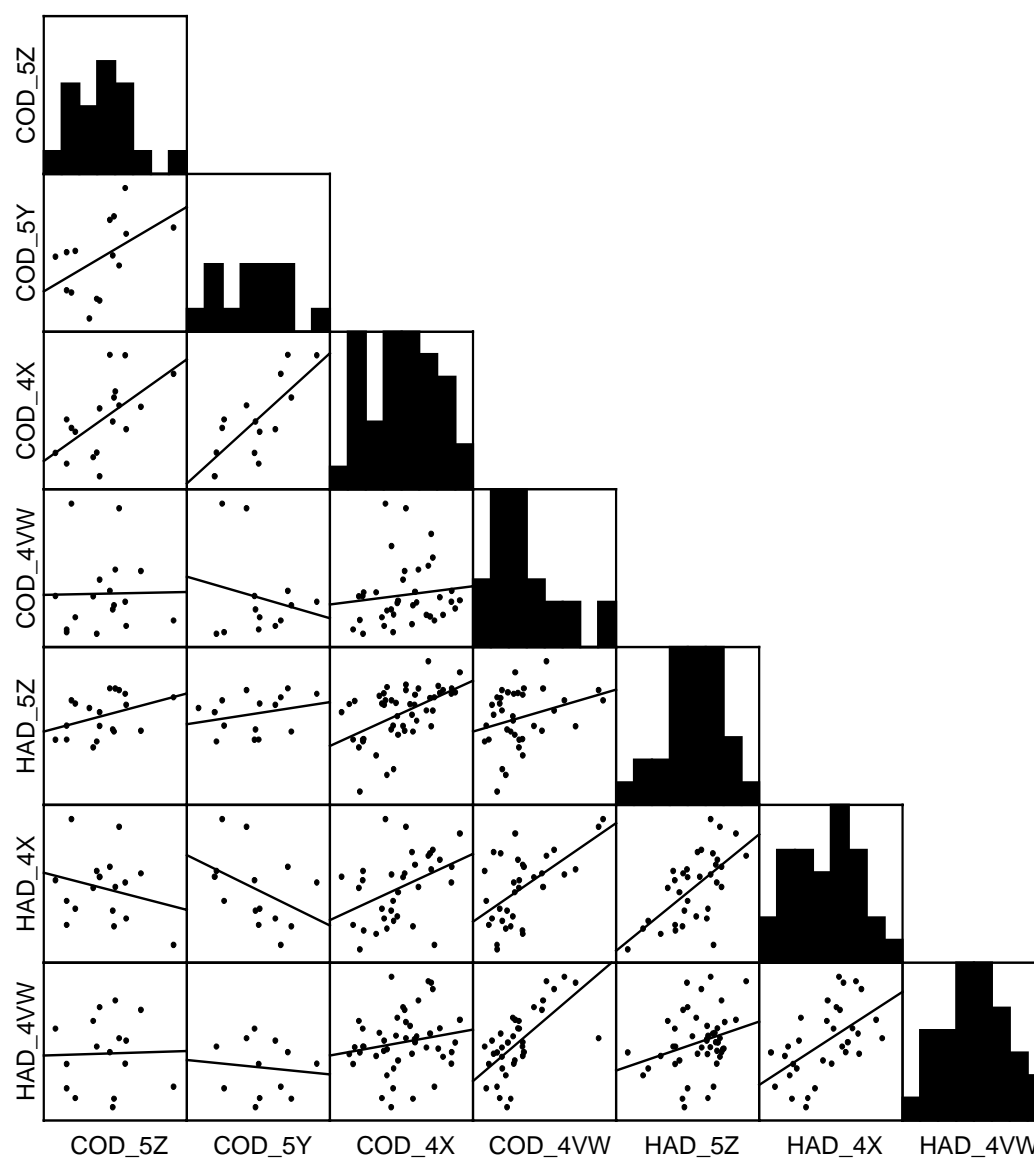


Figure 1.3.7. Pair-wise correlations between $\log(R/SSB)$ (recruitment, millions of age 1 fish/SSB, thousands of metric tons) of cod and haddock stocks (7) in the Georges Bank (5Z), Gulf of Maine (5Y), Browns Bank (4x), and E. Scotian Shelf (4VW) areas. Data are given only for stocks which are assessed with VPA.

Georges Bank Haddock

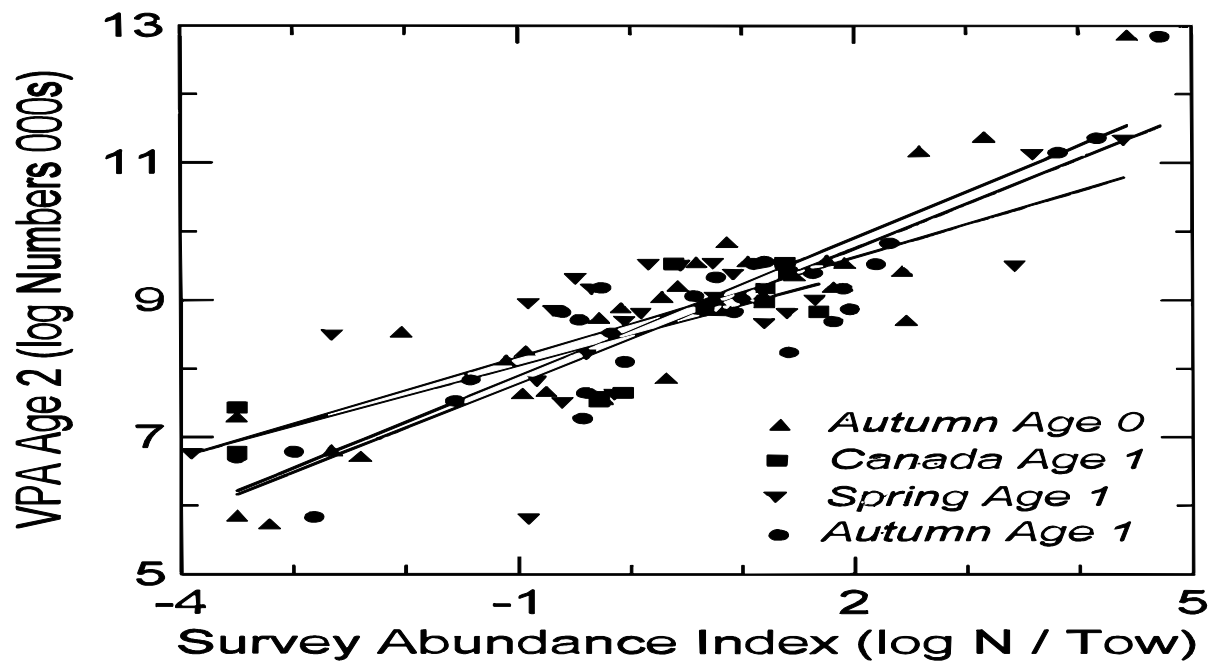


Figure 1.3.8. Relationship between bottom trawl survey indices of abundance and estimates of year class size from VPA for haddock on Georges Bank, 1963–1997. Survey indices are stratified log(numbers) per standardized tow for four survey series (autumn surveys at age 0; Canadian spring surveys at age 1; USA spring surveys at age 1, and USA autumn surveys at age 1). Year class size at age 2 is log[numbers, thousands], estimated from VPA.

2 Analysis of the 1960s and 1970s ocean climate in the Scotian Shelf, Georges Bank and Gulf of Maine

2.1 The long-term hydrographic variability on the Scotian Shelf and Gulf of Maine and their causes with special emphasis on the cool period of the 1960s

K. Drinkwater and B. Petrie

Examination of temperature and salinity data from the Scotian Shelf, Gulf of Maine, and adjacent continental slope has shown that the most dominant low-frequency event over the past half century was a cooling and subsurface freshening of the water masses from the early 1950s to the mid-1960s followed by a rapid reversal of these trends (Figures 2.1.1 and 2.1.2). The decade of 1960s was the coolest period on record in most areas from the Laurentian Channel to the Middle Atlantic Bight. The cooling was observed throughout the water column. Detailed investigations of the conditions in Emerald Basin in the center of the Scotian Shelf revealed that the largest amplitude of the low-frequency signal occurred at 100 to 150 m. This is the depth of the sill separating the offshore slope waters from the basin and suggested that the source of the cooling was advection from offshore. Studies of air-sea heat fluxes confirm that local atmospheric forcing can not account for observed interannual temperature changes on the Scotian Shelf and Gulf of Maine. In support of the offshore advection hypothesis, the largest temperature and salinity changes between 1952 to 1967 was 4.6°C and 0.7 psu, respectively, observed at about 100 m over the continental slope. Exchanges with shelf waters and vertical mixing gave rise to the upper surface layer manifestation of this variability over the shelf.

Cause of the changes in the slope waters were also investigated. The slope water off the Gulf of Maine and Scotian Shelf is observed to be a combination of Labrador Current deep water and North Atlantic Central Water. The 1960s was found to be a period of stronger Labrador Current with the transport in the deep (100-300 m) layer increasing from $1 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ in the early 1950s when conditions were warm on the Scotian Shelf to $4 \times 10^6 \text{ m}^3 \text{ s}^{-1}$ in the mid 1960s when conditions were cool. A simple model that accounts for this variation of transport and has a constant entrainment of North Atlantic water indicates the changes in the westward flow of the Labrador Current was the major contributor to the observed temperature and salinity fluctuations in the waters along the continental slope of the Scotian Shelf and Gulf of Maine, and subsequently on the shelves themselves. This work has been published by Petrie and Drinkwater (1993).

One other important cooling event on the Scotian Shelf and in parts of the coastal regions of the Gulf of Maine

was also described. This cooling occurred in the mid-1980s and has persisted through to present. It was most pronounced in the northeastern Scotian Shelf and has led to documented cases of the extensions in the range of certain species in the northeastern Shelf such as capelin (Frank *et al.*, 1996) and snow crab (Tremblay 1997). The cold was primarily confined to the cold intermediate layer of the shelf (from 50 m to depths of 100 to 200 m depending upon location). Similar cooling has been observed in the Gulf of St. Lawrence and off southern Newfoundland suggesting that advection of shelf waters may play an important role in the cause of this event. During the time of this cooling, the slope waters were anomalously warm and hence could not have been a cause of the cooling event.

2.2 Recent investigations of hydrographic and related variability in the Scotian Shelf and Georges Bank region

J. W. Loder, E. A. Gonzalez, C. G. Hannah, and B. D. Petrie

Aspects of decadal and interannual environmental variability in the Scotian Shelf and Georges Bank region being investigated in Canada and US GLOBEC are described.

Composite 3-d seasonal hydrographic fields for the cold 1960s and warm 1970s have been obtained to evaluate the spatial structure of the cold period described by Petrie and Drinkwater (1993) and associated circulation changes. Temperature and salinity changes are largest in the slope region for the surface, and along the shelf edge (extending into the Mid Atlantic Bight) and in deep channels and basins for the bottom. The 1960s subsurface temperature decrease was 2-3°C on the southern flank of Georges Bank. A similar change occurred around 1940. Geostrophic computations on the composite fields indicate increased southwestward baroclinic transport along the shelf edge and upper slope during the cold period which is being investigated further using a 3-d circulation model (see Shore *et al.*, Section 2.3) and individual-year geostrophic computations (below). Historical nutrient and oxygen data indicate lower nitrate and higher dissolved oxygen concentrations in the region during the cold 1960s, especially at depth.

Indices for hydrographic and baroclinic circulation variability on Georges Bank during 1977-87 springs are being developed for input to the interpretation of gadoid early life stage variability during the MARMAP years (see Lough and Berrien Section 3.6). Hydrographic structure and geostrophic flow have been estimated for March-April and May-June on sections across the

Northeast Peak spawning ground and the southern flank larval drift route. The largest hydrographic anomaly was an increased extent of cool shelf water in 1978, while the largest transport anomalies were increased south-westward flow in 1983 and 1987 and reduced flow in 1985.

Interannual hydrographic and transport variability on the Scotian Shelf are being investigated using geostrophic computations on about 100 occupations of the Halifax hydrographic section during 1950-1996, Halifax coastal sea level and Sable Island wind stress data. Initial indications are that the 1960s cooling occurred through two primary pulses of cold southwestward flow along the upper slope and subsequent intrusion into Emerald Basin, during the winters of 1958-1959 and 1963-1964. It is interesting that these pulses occur near minima of the North Atlantic Oscillation, suggesting that the Marsh *et al.* (1999) subpolar gyre extension mechanism may have contributed. Coastal sea level at Halifax doesn't show positive anomalies during the 1960s cold period as would be expected if a cross-shelf (baroclinic or barotropic) pressure gradient change were predominant, but does show negative (along-shelf) anomalies relative to St. John's which are being investigated.

The 3-d barotropic model solutions of Greenberg *et al.* (1997) are being used with Sable Island wind stress to estimate monthly changes in wind-driven transport across selected sections during 1960-1992. For southern Georges Bank in March-April, the along-shelf transport anomalies include increased southwestward flow to the Mid Atlantic Bight in 1987 (haddock larval advection; Polacheck *et al.* (1992) and reduced flow in 1982 (Lough *et al.*, 1994).

2.3 Circulation modelling studies in the Scotian Shelf - Gulf of Maine region

Jennifer Shore, Charles Hannah, John Loder, and Chris Naimie

Climatological fields show Georges Bank lies in a shelf regime with strong competing influences from subpolar shelf water to the north and slope water (mixed with subpolar and subtropical) to the south, with additional seasonal variations in temperature and coastal runoff.

Climatological solutions for four bimonthly seasons have been computed on a domain covering the Scotian Shelf - Gulf of Maine system from the Banquereau line down to Cape Cod. These solutions are an extension of the solutions described in Naimie (1996) and were computed using a methodology similar to the one described therein.

Statistics show that there is very good agreement with moored current meter measurements in SW Nova Scotia similar to the "Naimie" solutions on Georges Bank, but poorer agreement on Sable Island Bank. Particle tracking using the model flow fields show potential pathways exist for zooplankton supply to Browns Bank from larval

drift from the Scotian Shelf to Georges Bank (Figure 2.3.1). Further, decadal-scale hydrographic solutions were also modelled (using a similar methodology) for two distinct cold and warm periods representing the colder 1960s and warmer 1970s. These solutions were used to estimate circulation and transport differences between the two periods. There is a change in transport over the upper slope of Georges Bank in both winter and spring on the order of 1 Sv between the warm and cold periods (stronger in the cold period) which appears to be largely associated with the local density field (Figure 2.3.2). Inside the 100 m isobath, the changes are much smaller and differ with season. These smaller changes are likely include contributions from both the shelf edge density field and barotropic through flow.

2.4 Model estimates of interannual stratification variability on southern Georges Bank, 1985-1995

J. J. Bisagni

One-dimensional energy models have long been shown to describe the location of tidal mixing fronts, separating well-mixed from stratified waters on mid-latitude continental shelf regions, such as Georges Bank, from spring-fall. The same models can also be used to describe adjustments of the fronts and changes in density stratification to time-dependent variability of surface heating, tidal stirring and wind mixing over a broad range of time scales. In this study, input time series of five-day averaged vertical heat flux, tidal stirring and wind mixing, together with a simple one-dimensional energy model incorporating the effects of a bottom boundary layer, spatially-varying bottom roughness and spatially-varying but constant tidal mixing efficiencies are used to examine interannual variability of monthly-averaged stratification on southern Georges Bank from 1985-1995 relative to a set of eleven-year (1985-1995) monthly mean values. Results show no interannual variability for water depths of less-than 60 m where the water column remains well-mixed throughout each year, in agreement with earlier work. Interannual stratification variability for water depths of 60-80 m and 80-100 m is greatest during summer and early fall with reduced variability for other months. Most of the interannual stratification variability variance (up to ~80%) can be explained by interannual heat flux variability with the remaining variance explained by interannual variability of wind mixing. Transient density stratification is apparent during neap tidal periods prior to the set-up of seasonal stratification for several of the years.

2.5 Hydrographic variability on the Northeast Shelf

David G. Mountain

Variability on the water properties on the northeast US continental shelf over recent decades are reviewed. The primary available data sets are:

- 1) the NEFSC bottom trawl surveys (1963 to present);
- 2) the MARMAP data set (1977-1987);
- 3) the "Colton" data set (1964-1966);
- 4) Woods Hole water temperatures (1963 - present).

The Woods Hole water temperature record indicated a progressive warming from the 1960s to the 1990s during the winter, with about a 2°C increase over that period. This likely reflects local atmospheric conditions. The shelf wide hydrographic data indicate:

coldest conditions in the late 1960s and warmest in the mid-1970s, with intermediate and varying conditions since the late 1970s;
 variability in average salinity of order 0.5 PSU over periods of a 1-3 years;
 a decrease in salinity in the region from 1995 into 1998. While this is believed due to increased contribution of freshening from the Labrador Sea, the t/s relationship does not indicate a cold, Labrador Slope Water influence, as was seen in the cold period of the 1960s;
 a recent (in 1998) change in the Slope Water entering the Gulf of Maine which does indicate an influence of cold, Labrador Slope Water;

The volume of shelf water in the Georges Bank/Middle Atlantic Bight region exhibited large variations in the MARMAP data set, with large volumes in 1978 and 1987 and low values in 1985/1986. The changes are believed due in large part to changes in the inflows of water to the Gulf of Maine/Georges Bank system from the Scotian Shelf and through the Northeast Channel. The associated changes in flow are believed to have important implications for the advection of ichthyoplankton on Georges Bank.

2.6 Inventory of long-term physical oceanography time series and data sources for Scotian Shelf/Gulf of Maine/New England Shelf region

Bob Beardsley and Steve Lentz

This inventory (Appendix 2) presents a simple listing of climatologies and long-term physical oceanographic and atmospheric data sets for the Scotian Shelf/Gulf of Maine/New England Shelf region. The listing is not comprehensive nor complete, but does attempt to include those data sets known to the participants at this meeting, and provide names of individuals in {} to contact for more information.

2.7 Recent temperature, salinity changes on the Scotian Shelf and Gulf of Maine-Harping back to the 1960s?

K. Drinkwater, D. Mountain, and A. Herman

Hydrographic data collected during the autumn of 1997 to the spring of 1998 indicate the presence of anomalously cold, fresh waters along the edge of the Scotian Shelf (Figure 2.7.1). First observed in September in the northeast off Banquereau Bank, by October they had reached south to Emerald Bank on the Halifax Line. Minimum temperatures of near 1°C were observed at 75 m while at depth (100-300 m) temperatures were <7°C. Throughout most of the 1970s, 1980s and 1990s, the deep waters found along the shelf edge had been significantly warmer (>8°C). By December, the mean circulation had carried the cold water at 50 to 100 m depth around Emerald Bank to its inshore edge. Cold water (temperatures <7°C) was also beginning to penetrate into Emerald Basin at depths of 100-200 m although conditions in the central and northern regions were unaffected as temperatures remained above 9.5°C. By February, however, the entire Basin had been flushed as temperatures and salinities fell, e.g., at 250 m to 7.3°C and 34.3 from 9.8°C and 34.8 psu in December. Densities between 100 and 200 m decreased but did not change significantly below 200 m. In April there was an additional decrease of 1°C and 0.2 psu in temperature and salinity, respectively, indicative that further flushing of the Basin had taken place.

The cold water observed off the Scotian Shelf penetrated further southward. In January 1998, it reached the northern side of Northeast Channel and was entering the Gulf of Maine. Temperatures continued to decrease in the Channel during the spring and remain cold. By February, the southern flank of Georges Bank was flooded with the cold water. On the southwestern flank, they were replaced with warmer water by April but on the southeastern flank conditions remain cold.

Temperature, salinity characteristics (Figure 2.7.2) reveal that the waters in the deep basins of the shelf and along the shelf edge during the recent events, match closely those observed during the 1960s, a previous period of very cold conditions. This water is identified as slope water of Labrador Current origin. Cause of the appearance of this water so far south is believed to be due to an increase in the transport of the Labrador Current. Fluctuations in the strength of this current have been shown to be linked to the large-scale atmospheric circulation patterns as reflected in the North Atlantic Oscillation (NAO) index. The flow tends to increase when the index is low, which is associated with a decrease in the strength of the Icelandic Low. It is speculated the recent surge of cold Slope Water southward may be a delayed reaction to the low NAO index of the last two years.

2.8 Shell-derived seasonal temperature histories (1958-1982) from Georges Bank and Scotian Shelf regions

Christopher Weidman and Glen Jones

Continuous, high-temporal resolution and multidecadal marine temperature records are rare to non-existent for most ocean regions. Therefore, the improvement and application of paleoceanographic methods provides a vital link in our ability to reconstruct and understand past ocean climate conditions. This study focused on temperature conditions in the Georges Bank and Scotian Shelf regions during the mid-1960s extreme “cold” period and its contrast with “warmer” conditions in the 1970s. Proxy bottom temperature time-series (1958–1982) were reconstructed for four sites on the continental shelf of the northwestern Atlantic: 1) Nantucket Shoals (65 m), 2) Georges Bank - Northern Edge (61 m), Georges Bank - Southeastern Flank (70 m) and 4) Scotian Shelf - Middle Bank (62 m). These time series present a continuous (25 year) seasonal (annual mean, maximum and minimum) record and were derived from the oxygen isotope (^{18}O) analysis of the annual growth bands of live-collected shells from the long-lived bivalve *Arctica islandica*. Ocean paleotemperature reconstructions using ^{18}O compositions of biogenic marine carbonates has a half-century history (Wefer and Berger 1991), and verification of its application to the mollusc *A. islandica* has been documented (Weidman *et al.*, 1994).

The shell-derived bottom temperature records show that the 1960s were indeed a period of extreme cold in the shelf bottom waters, and that the 1970s were much warmer in general (Figure 2.8.1). They also indicate that Scotian Shelf cold and warm anomalies tend to precede those in the Georges Bank region by 2–3 years. However, the temperature relationship between the two regions, as well as among sites within the Georges Bank region is not simple, and there are important differences in the anomaly patterns between records (Figure 2.8.2). The bottom temperature records show a strong correspondence with other historical ocean temperature records (Emerald Basin and Boothbay Harbor) and with relevant climate records such as New Haven air temperatures, NAO index and East Coast storm frequencies (Davis *et al.*, 1993). For example, during the period 1958-1982, Georges Bank and Scotian Shelf cold anomalies are positively related with low NAO index years (Figure 2.8.3) and increased storm frequencies (Figure 2.8.4), while warm anomalies correspond to high NAO indices and decreased storminess.

2.9 Global modes of ENSO and non-ENSO sea surface temperature variability

D. B. Enfield¹ and A. M. Mestas-Nunez²

¹NOAA/AOML, Miami, Florida 33149, USA. ²CIMAS, University of Miami, Miami, Florida 33149, USA.

El Nino Southern Oscillation (ENSO) is a global phenomenon with significant phase propagation within and between basins. We capture and describe this in the first mode of a complex empirical orthogonal function (CEOF) analysis of sea surface temperature anomaly (SSTA) from the mid-19th century through 1991 (Figure 2.9.1). We subsequently remove the global ENSO from the SSTA data, plus a linear trend everywhere, in order to consider other global modes of variability uncontaminated by the intra- and inter-basin effects of ENSO.

An ordinary EOF analysis of the SSTA residuals reveals three non-ENSO modes of low-frequency variability that are related to slow oceanic and climate signals described in the literature. The first two modes have decadal-to-multidecadal time scales with high loadings in the Pacific. They bear some spatial similarities to the ENSO pattern but are broader, more intense at high latitudes, and differ in the time domain. A CEOF analysis confirms that they are not merely the phase-related components of a single mode and that all three modes are without significant phase propagation. The third mode is a multidecadal signal with maximal realisation in the extratropical North Atlantic southeast of Greenland (Figure 2.9.2). It is consistent with studies that have documented connections between North Atlantic SSTA and the tropospheric North Atlantic Oscillation (NAO). All three SSTA modes have mid-tropospheric associations related to previously classified Northern Hemisphere teleconnection patterns. The relationships between SSTA modes and tropospheric patterns are consistent with the ocean-atmosphere interactions discussed in previous studies to explain low-frequency climate oscillations in the North Pacific and North Atlantic sectors. The first three leading modes of non-ENSO SSTA are most related, respectively, to the tropospheric patterns of the Pacific North American (PNA), the North Pacific (NP) and the Arctic Oscillations (AO), respectively. The 500 hPa pattern associated with the third SSTA mode also bears similarities to the NAO in its Atlantic sector. This North Atlantic mode has a region of high, positive SSTA loadings in the Gulf of Alaska, which appear to be connected to the North Atlantic SSTA by a tropospheric bridge effect in the AO.

A detailed account of our findings is given in Enfield and Mestas-Nunez (1999).

see <http://www.aoml.noaa.gov/phod/docs.html>).

2.10 Summary

The following is a summary of the ocean climatology of the Northwest Atlantic Shelf focusing on the 1960s but extending to the present conditions. This summary is based on discussions that took place during the workshop and are discussed in more detail in the extended abstracts included in this report.

2.10.1 Oceanic climatology 1960s and 1970s

The 1960's decade was the coolest period on record in most areas from the Laurentian Channel to the Middle Atlantic Bight. Subsurface freshening of water masses co-occurred with the cooling period. Historical nutrient and oxygen data indicate lower nitrate and higher dissolved oxygen concentrations in the region during the cold 1960's, especially at depth. Rapid warming of the water column followed during the late 1960s and 1970s.

The cooling of the shelf waters in the 1960s is largely due to the presence of cold, fresher Labrador Slope waters offshore that subsequently penetrated onto the shelf. In support of this offshore forcing, the largest temperature and salinity changes observed were along the shelf edge of the Scotian Shelf to the Middle Atlantic Bight at depths of 100–300 m. Cold Labrador Slope water was replaced by Warm Slope water in the late 1960s and hence the shelf subsequently warmed.

Atmosphere-ocean heat flux over this region has been found to be insufficient to explain the observed low frequency temperature oceanic signal.

The cause of the presence of cold slope waters along the shelf edge off the Scotian Shelf and areas south during the 1960s is believed to be increased transport of the Labrador Current. In the deep 100–300 m layers, the Labrador Current transport near the Tail of the Banks has been estimated to be 1.6 Sv during the 1960s, and approximately 1.2 Sv higher than it was in the 1950s and 1970s.

Circulation models capture this increase in transport along the slope off the Scotian Shelf during the cold period with approximately a 1 Sv difference between the cold and warm periods. These changes appear to be related to the local density field and are observed during both winter and spring. Inside the 100 m isobath, the circulation changes between the two periods are much smaller and differ seasonally.

Past studies suggest an inverse relationship between the strength of the Labrador Current's southwestward transport and the NAO index. During the 1960's the North Atlantic Oscillation (NAO) was at its lowest point since the 1880s.

During the 1960's, winds were more strongly across-shore (toward the ESE) with a peak in (east coast) storm frequencies. The 1970's showed a minimum in storm

frequency, suggesting a possible inverse relation to the NAO index.

The observed temperature fluctuations in the 1960's and 1970's are captured by the shell-derived temperature records. These records indicate that the Scotian Shelf cold and warm anomalies tend to precede those in Georges Bank by 2–3 years.

Anomaly patterns in the shell-derived temperature records for the Scotian Shelf and Georges Bank have been found suggest that a post-1975 temperature drop observed on the Bank was not observed on the Scotian Shelf.

The combined Georges Bank shell records correlate positively with the NAO index (i.e., low temperatures occur when the NAO index is low).

2.10.2 Oceanic climatology from the MARMAP years (1977–1987) to the present

Since the mid 1970s conditions over the New England Shelf, Georges Bank and Scotian Shelf have been less extreme and more variable.

On the Scotian Shelf, cooling occurred in the mid-1980s and has persisted through to the present. The cold signal is primarily confined to intermediate layers (50 to 100 or 200 m) on the shelf and extends north to southern Newfoundland. During this cooling period, the slope waters have been anomalously warm suggesting that the cooling has not been related to advection of slope waters onto the shelf.

The volume of shelf water in the region of Georges Bank and the Middle Atlantic Bight was high during 1978 and 1987 and is likely related to increased inflows from the Scotian Shelf. The shelf water volume was low during 1985 and 1986.

Hydrographic sections on Georges Bank indicate that the largest hydrographic anomaly was an increased extent of cool shelf water in 1978, while the largest transport anomalies were increased southwestward transport along the shelf during 1978 and 1987. In contrast, 1985 and 1986 show transport minima. The fluctuations in transport can be related to retention on Georges Bank with higher retention during low southwestward transport conditions.

Coastal water temperature records collected at Woods Hole show monotonic warming in each of the decades from the 1960s to the 1990s. The overall 2°C warming over this period may reflect local atmospheric conditions.

On Georges Bank one-dimensional energy models have successfully described changes in stratification to time-dependent variability of surface heating, tidal stirring and wind-mixing. For the 1985–1995 time period,

no interannual variability was found for water depths less than 60 m. Interannual stratification variability is found for waters 60-100 m in depth and is greatest during summer and fall, and is related to variability in the interannual heat flux.

Beginning in 1995 there has been a significant reduction in salinity in the water column on Georges Bank and the Gulf of Maine.

Observed decreases in salinity between 1995 and 1997 do not fall on a 1960s T-S curve suggesting that the changes during this time period were not related to advective effects of the Labrador Current.

More recently, from fall of 1997 through the spring of 1998, cold Labrador Slope water has been observed penetrating into the deep basins of the Scotian Shelf and entering the Northeast Channel and Gulf of Maine. This cold signal had reached the southern flank of Georges Bank by winter of 1998.

The temperature and salinity characteristics of these (1997–1998) waters match closely those observed during the very cold 1960s. This southward surge of cold Labrador Slope water is believed to be due to an increase in the transport of the Labrador Current, which in turn may be linked to the low NAO index of the past two years.

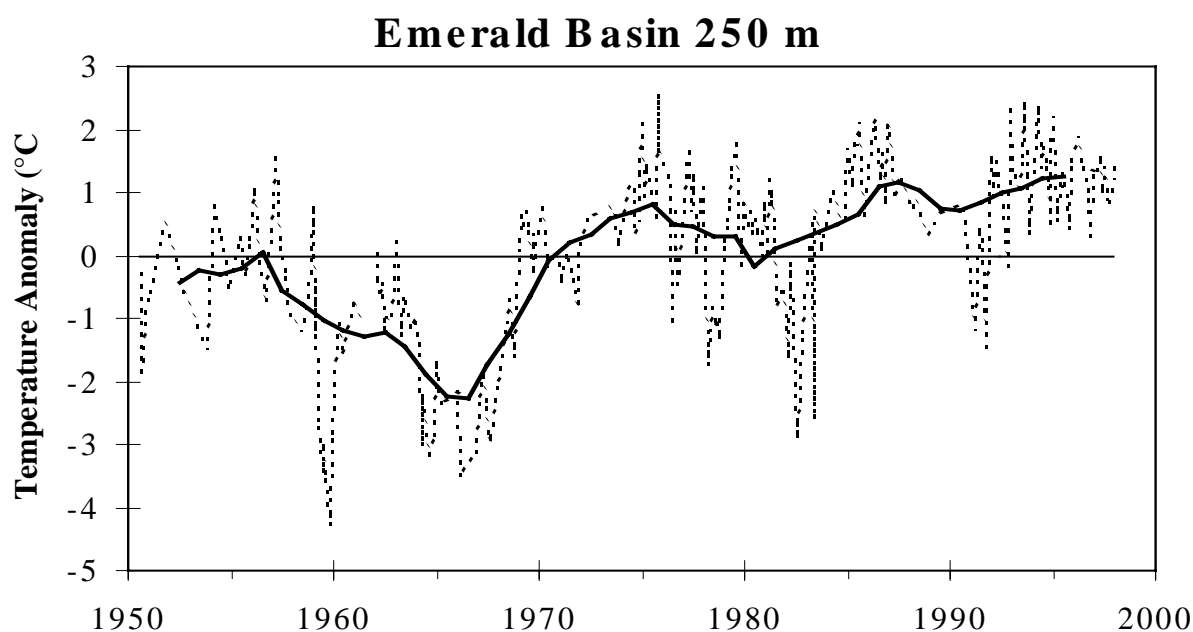


Figure 2.1.1. The temperature anomalies relative to the 1961–1990 means at 250 m in Emerald Basin in the center of the Scotian Shelf. The dashed lines connecting monthly mean temperature anomalies and the heavy solid line is the 5-year running mean of the annual anomalies. Note the extended cold period of the 1960s.

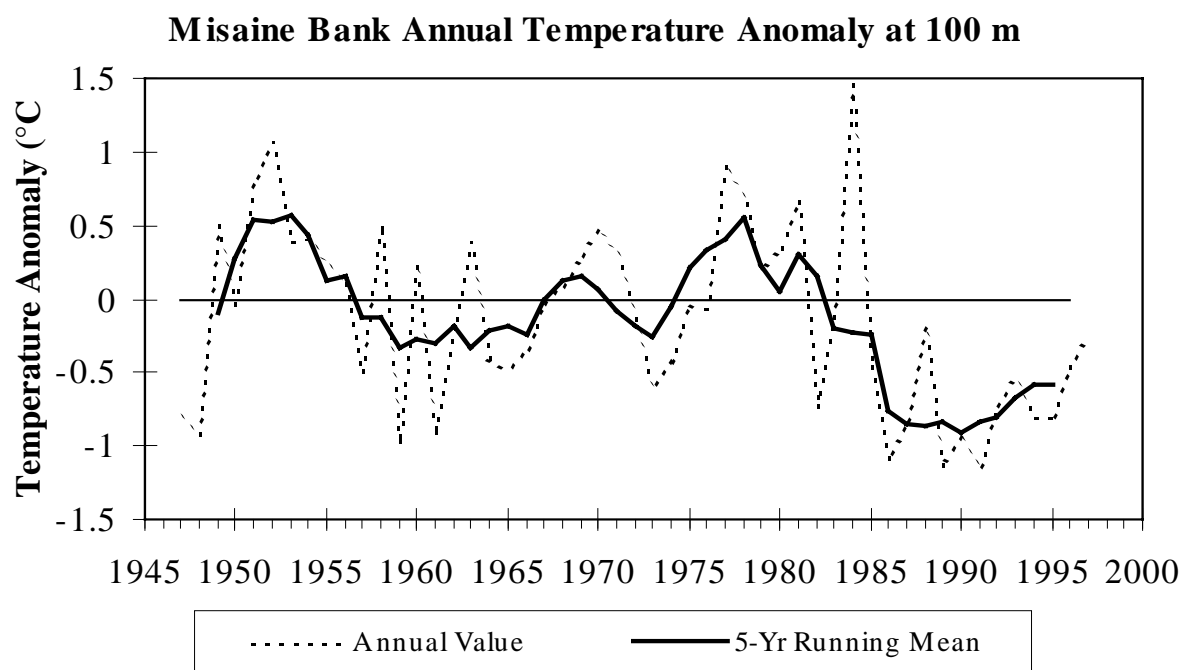


Figure 2.1.2. Annual and 5-year running mean of the temperature anomalies at 100 m on Misaine Bank in the northeastern Scotian Shelf. Note the very cold conditions that have persisted since the mid-1980s.

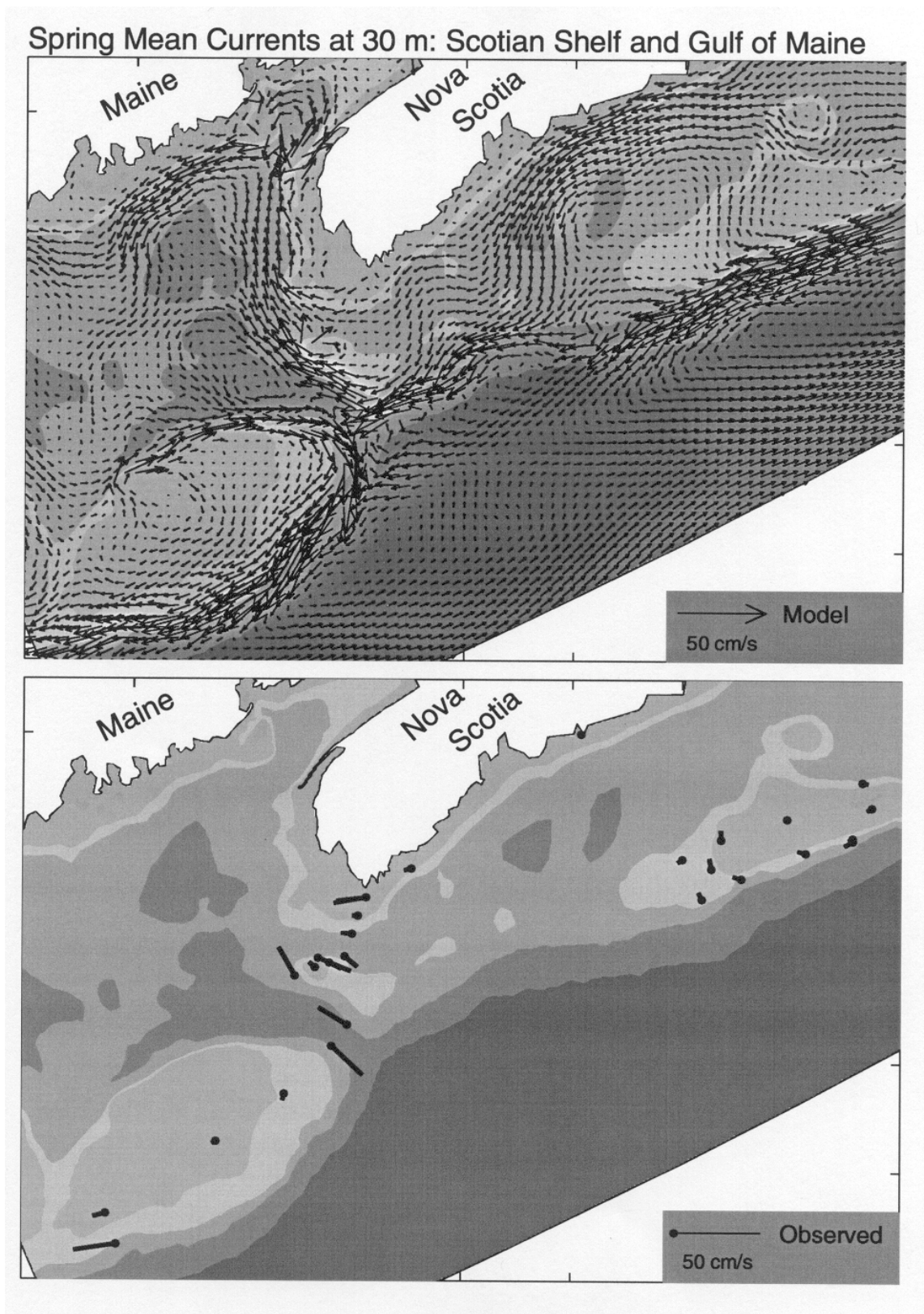


Figure 2.3.1. Mean spring current vectors at 30 m in the Scotian Shelf and Gulf of Maine regions based on numerical simulations (upper) and observed current meter data (below).

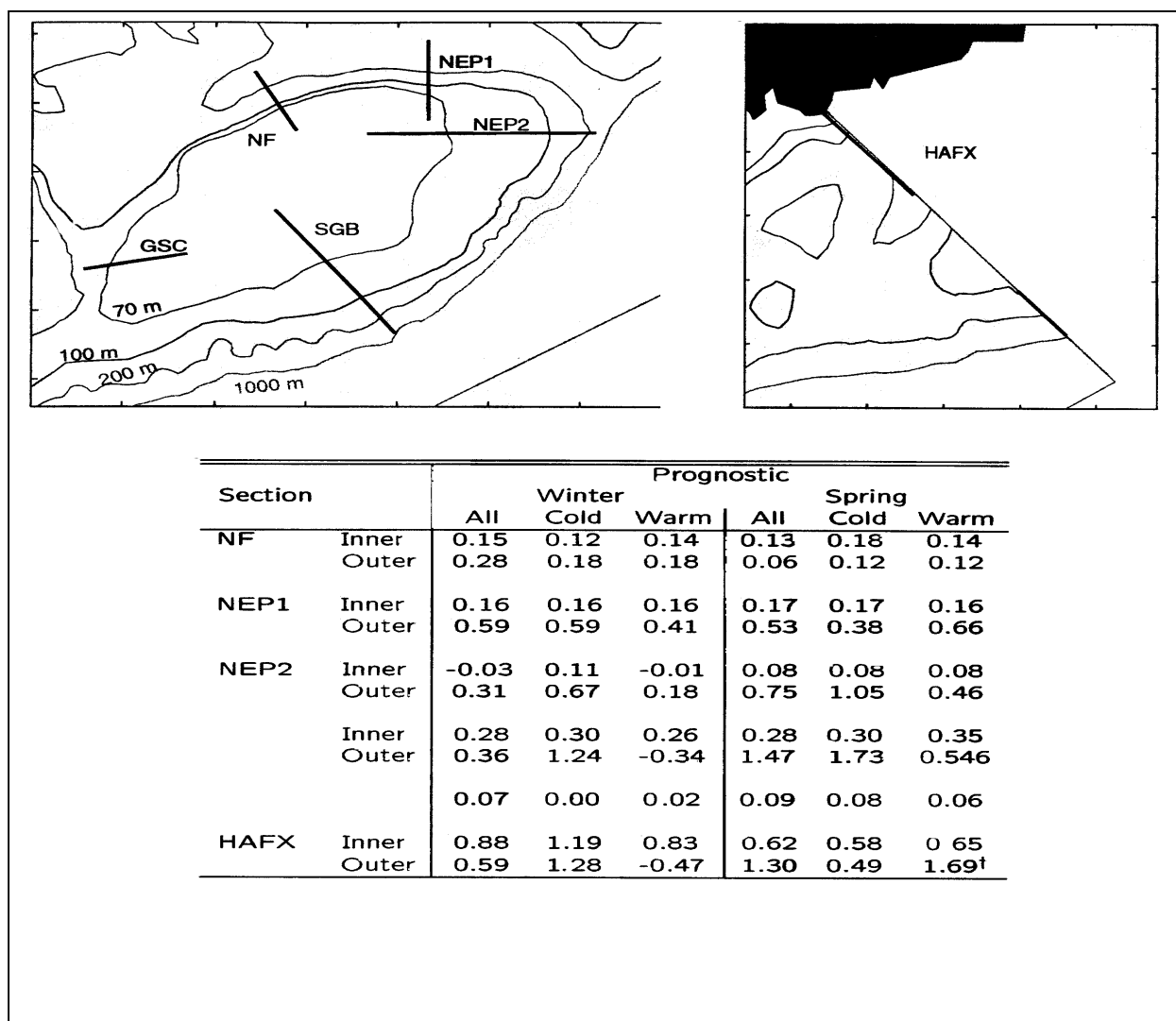


Figure 2.3.2. Transport through key sections in the Georges Bank and Scotian Shelf regions for decadal average fields. Positive clock-wise flow around the Bank and downstream through the Halifax line. Climatological wind forcing is used, units are in Sv. †Local corner feature.

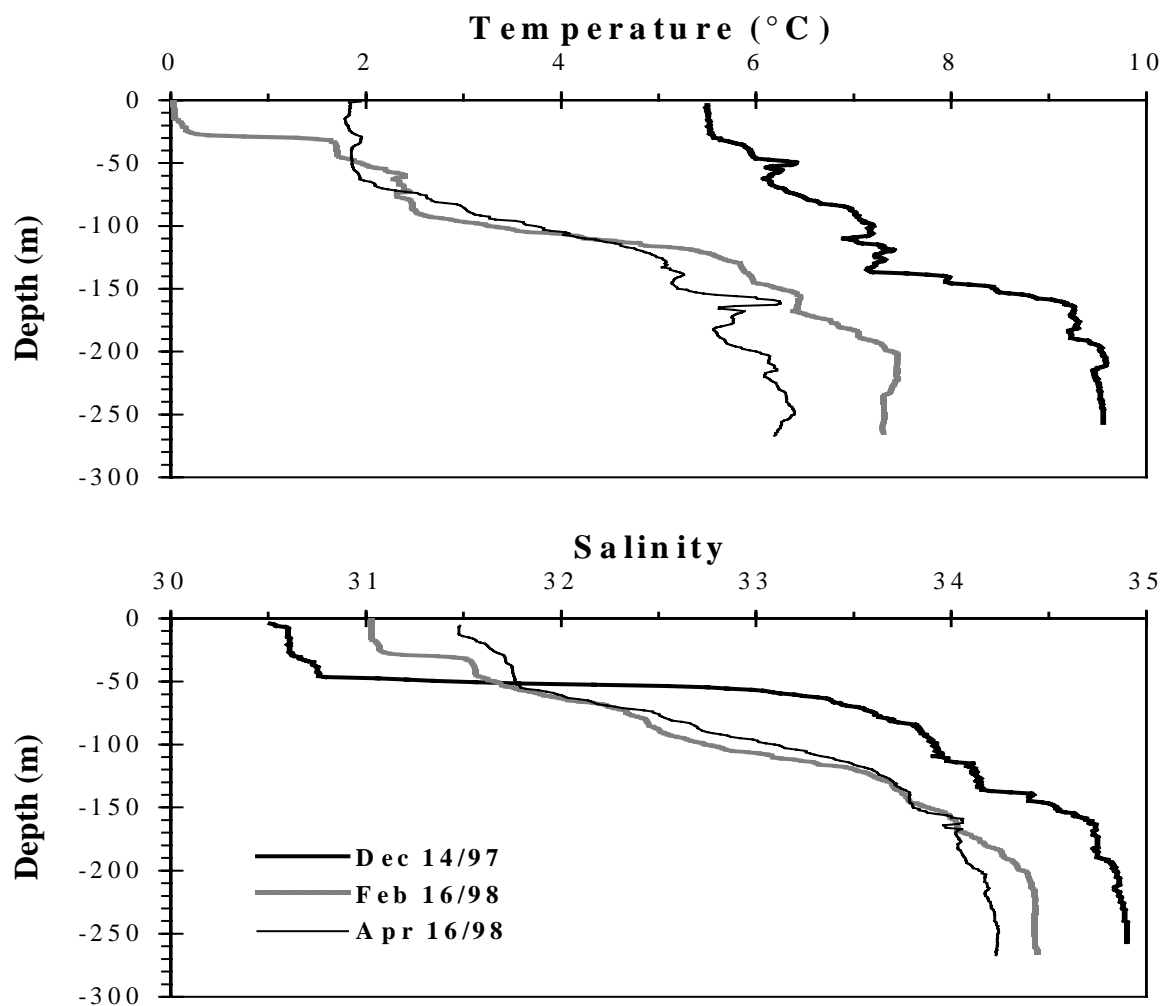


Figure 2.7.1. Temperature and salinity profiles taken in Emerald Basin in December, 1997, and February and April, 1998.

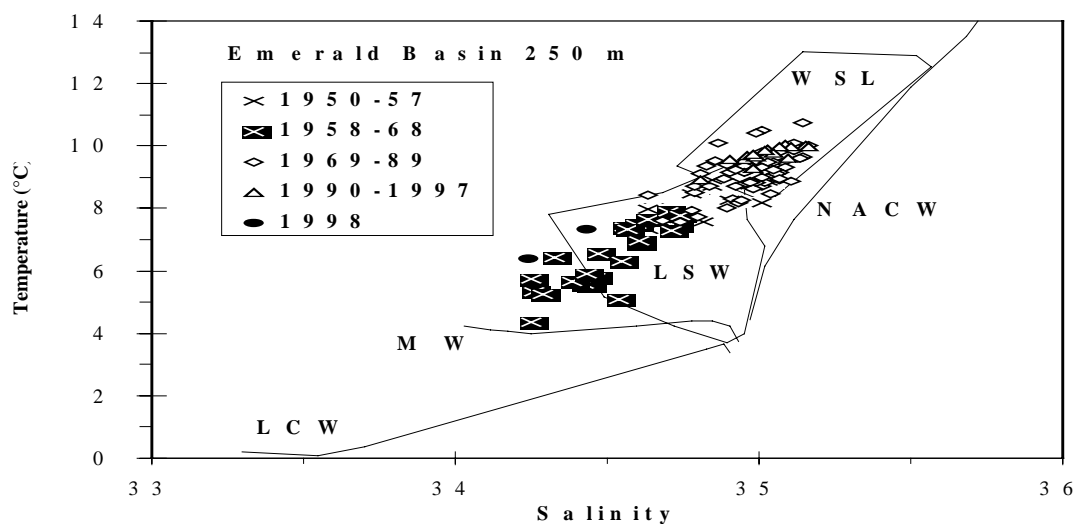


Figure 2.7.2. The T,S diagram for the waters at 250 m in the Emerald Basin. The irregular shaped polygons indicate the characteristics of warm slope water (WSL) and Labrador slope water (LSW). The lines show the North Atlantic Central waters (NACW), Labrador Current water (LCW) and the mixture between the two (MW).

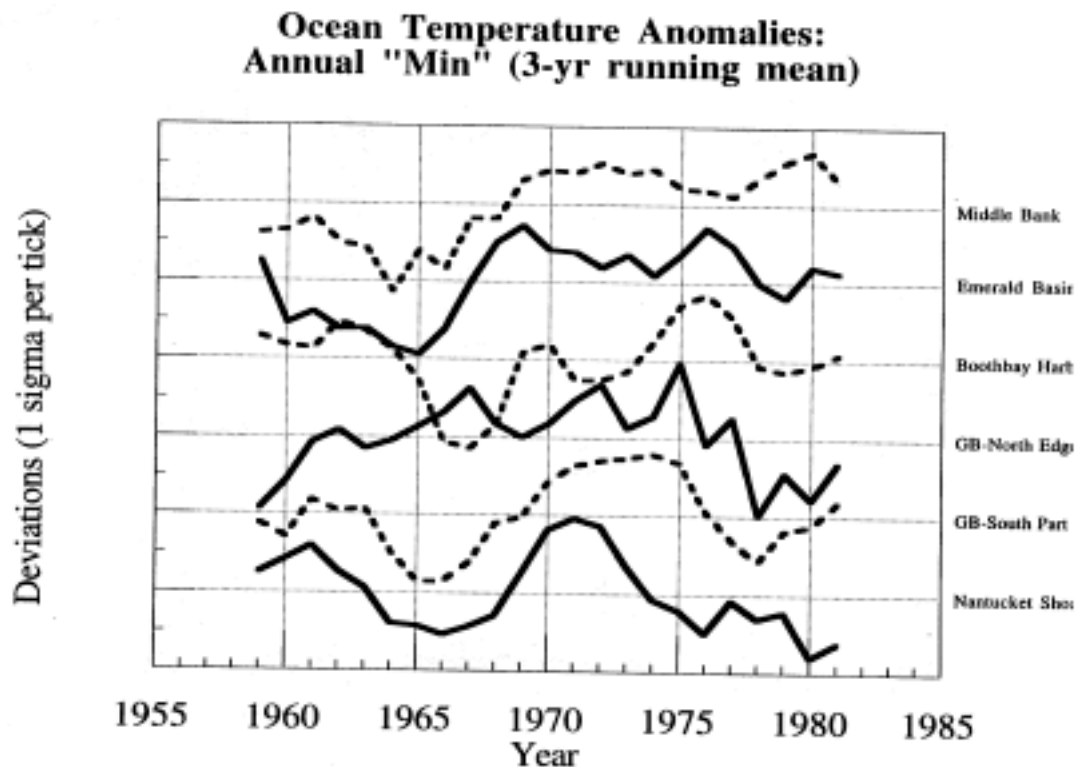


Figure 2.8.1. Ocean temperature anomalies derived from oxygen isotope ratios in ocean quahog shells for various locations on Georges Bank, and the Scotian Shelf. Data are 3-year running means of the deviations from the mean of the minimum annual temperature recorded in the shells (1 standard deviation per tick mark). Additional temperature measurements from Boothbay Harbor and the Emerald Basin are given.

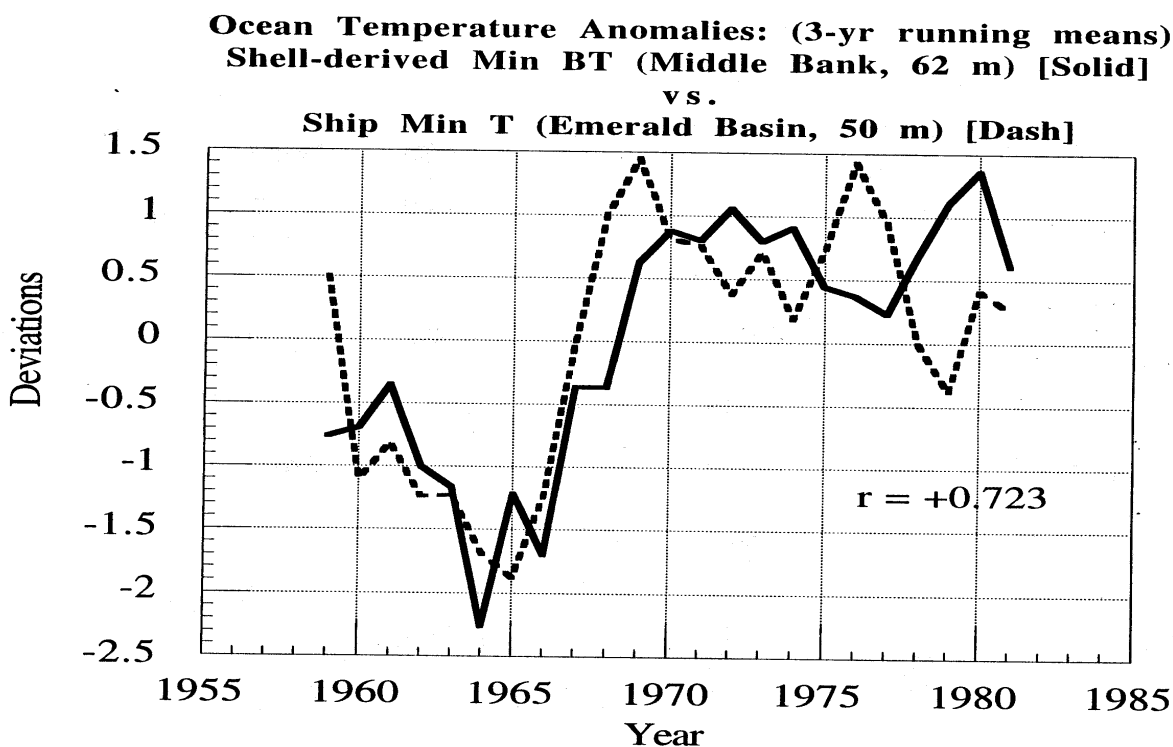


Figure 2.8.2. Anomalies in ship-based and shell-derived minimum bottom temperatures from the Scotian Shelf, Middle Bank (62 m), 1959–1981. Data are expressed as deviations from the long-term average annual minimum temperature.

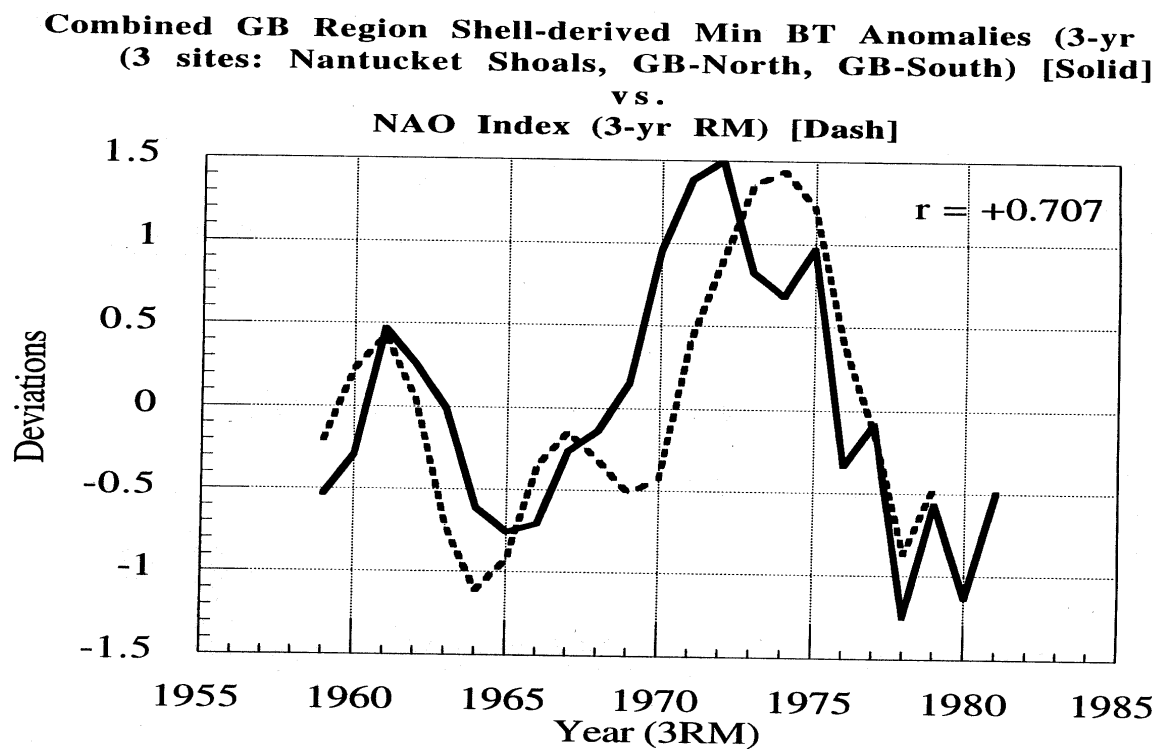


Figure 2.8.3. Anomalies in shell-derived minimum bottom temperatures from Georges Bank (three locations), 1959–1981, vs. the three-year running mean in the NAO regional index. Data are expressed as deviations from the long-term average. The Pearson correlation coefficient, r , is presented.

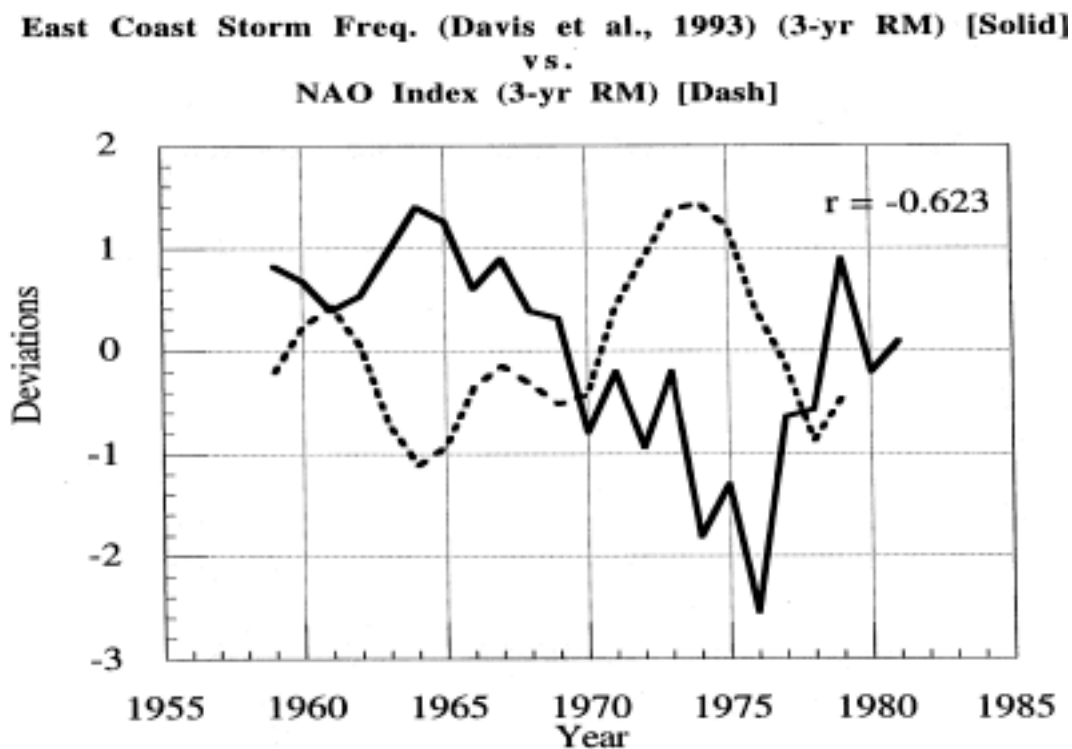


Figure 2.8.4. Deviations in East Coast (USA) storm frequency vs. three-year running mean of the regional NAO index, 1959–1981. The Pearson correlation coefficient, r , is presented.

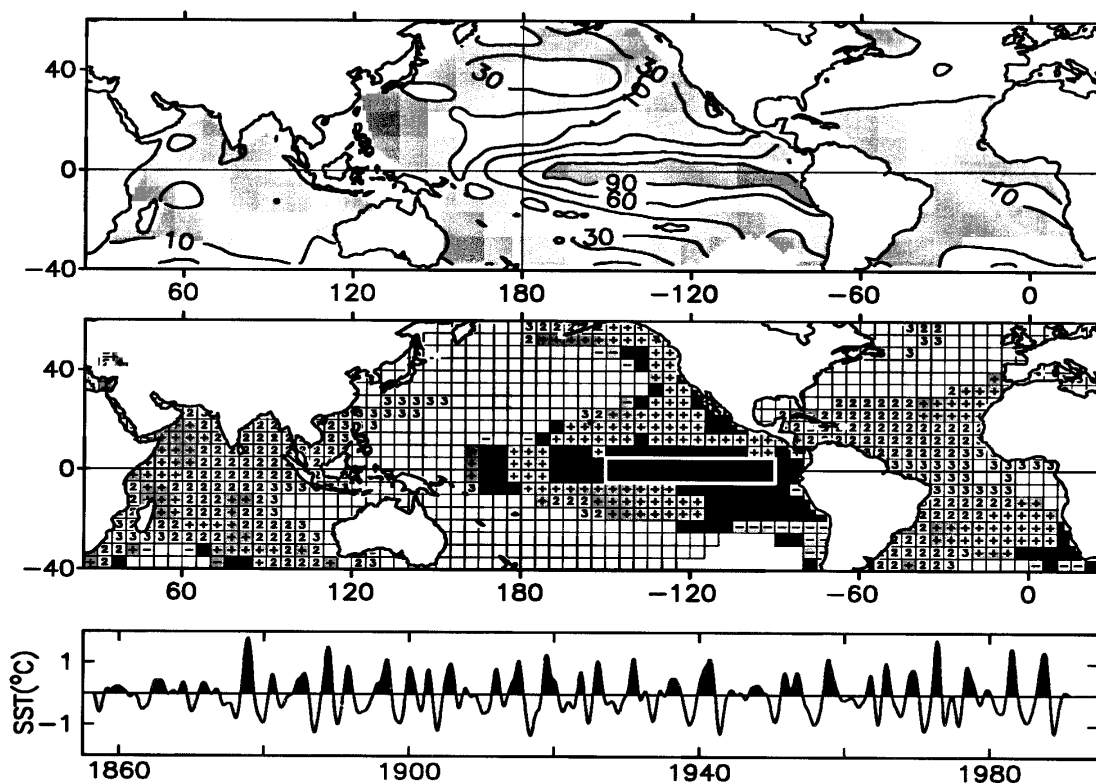


Figure 2.9.1. First complex empirical orthogonal function (CEOF), describing the global ENSO variability. Upper: spatial distribution of the response with respect to the modal reconstruction over the NINO3 index region (white rectangle, middle panel); contours shown are 10, 30, 60, and 90. A score of 100 is the response of the NINO3 data average. Middle: spatial distribution of phase lag (seasons); +/- indicates that the data lag/leads NINO3 (lower panel) by one season and positive numbers indicate data lags of more than one season. Lower: temporal reconstruction of the mode-related variability over the NINO3 index region.

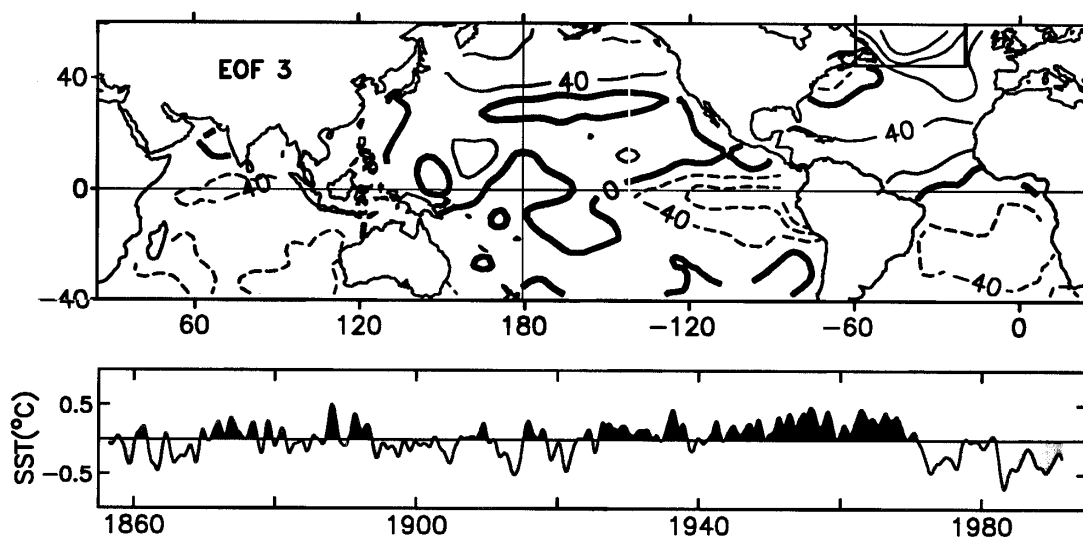


Figure 2.9.2. Third empirical orthogonal function (EOF) of the non-ENSO residual data set, describing the Atlantic multidecadal variability. Upper: spatial distribution of the response with respect to the modal reconstruction over the index region (rectangle); contour interval is 40 and a score of 100 is the response of the data average over the index region. Dashed contours are negative. Lower: temporal reconstruction of the mode-related variability over the index region.

3 Conditions contributing to the formation of outstanding year classes during the 1960s and 1970s

3.1 Overview

Information on year class strength for gadoids in the region is provided in Tables 1.3.2 to 1.3.4 and Figures 3.1.1 to 3.1.3. These data include both absolute (VPA-based) and relative indices of year class size, where appropriate. Based on these data, relatively large cod year classes appear to have been produced in the early 1960s and late 1970s on Browns Bank and the Eastern Scotian Shelf, and (based on indices from trawl surveys) in 1966, 1971, 1975 on Georges Bank, and 1971, 1973, 1977 and 1979 in the Gulf of Maine. For haddock, very strong 1962 and 1963 year classes were produced on Georges Bank, Browns Bank and the Eastern Scotian Shelf (Figure 3.1.3). In all these areas, haddock year class strengths were very low from 1964-1974 (Georges Bank), 1965-1971 (Browns Bank) and 1965-1974 (E. Scotian Shelf). Relatively strong year classes were produced on Georges Bank in 1975 and 1978; there was a succession of moderate to strong cohorts in the late 1970s on Browns Bank, and increasingly good haddock recruitment after 1973 on the E. Scotian Shelf.

Spawning stock biomasses for the various cod and haddock stocks are plotted in Figures 3.1.4 and 3.1.5. All stocks exhibited relatively sharp declines in SSB during the mid- to late 1960s, and especially haddock. These declines were primarily due to very intensive fisheries, resulting from intensive effort by distant water fleets (Boreman *et al.*, 1997). All stocks likewise exhibited some corresponding increase in spawning stock biomass in the mid- to late- 1970s, as a result of improved recruitment.

Patterns in recruitment survival ($\log[R/SSB]$) are plotted in Figures 3.1.6 and 3.1.7, respectively. For Gulf of Maine and Georges Bank cod stocks, the trawl survey indices of spawning stock biomass and recruitment strength (Table 1.3.4) are plotted (Figure 3.1.6). A LOWESS smoother with relatively low tension (0.2) was fitted through the points. The data show both high frequency (year-to-year) and low frequency (decadal-scale) variability. The indices based on survey data alone exhibit considerable high-frequency variation (southern cod stocks). Cod stocks on Browns Bank and in the Gulf of Maine show reduced recruitment survival (low-frequency response) in the 1960s, followed by improvement in the 1970s. For all cod stocks, the 1970s showed improved recruitment survival.

In the case of Scotian Shelf stocks, record recruitment survival declined in the late 1970s to early 1980s. Georges Bank and Gulf of Maine cod stocks showed the highest level of low frequency recruitment survival in the 1980s (Figure 3.1.6).

All haddock stocks showed pronounced declines in high-frequency and low frequency-signals in recruitment survival in the mid-late 1960s (Figure 3.1.7). The decline was approximately concordant, perhaps occurring a bit later on the Eastern Scotian shelf. Recruitment survival improved substantially in the early- mid-1970s, to the long-term average (Georges Bank and Browns Bank) or to record high levels (Eastern Scotian Shelf). Recruitment survival subsequently declined in the late 1970s- early-1980s, and has improved in the 1990s for all haddock stocks.

This section reviews available information for biotic and abiotic correlates to the observed fluctuations in recruitment and recruitment survival in the 1960s and 1970s.

3.2 Overview of Georges Bank and Gulf of Maine cod and haddock populations

R. Brown, R. G. Lough, R. Mayo, S. Murawski, L. O'Brien, F. Serchuk, and K. Sosebee

Populations of cod, and particularly haddock in the Georges Bank and Gulf of Maine areas have been intensively studied throughout this century, owing to their great economic importance (Figure 1.3.2). The precipitous decline in haddock landings in the late 1920s and early 1930s was thought to be related to reduced spawning stock size and discarding of large quantities of small fish (Herrington 1941). This "crisis" in the fishery resulted in the formation of a demographic study of haddock population dynamics (Herrington 1944; Clark *et al.*, 1982), as well as studies of factors influencing the early life history of the stock (Walford 1938; Chase 1955).

Information concerning the abundance and recruitment of Georges Bank and Gulf of Maine cod in the 1960s and early 1970s is based solely on research vessel survey indices, and total landings data (Figure 3.1.2 and 3.1.5). Some attempts have been made to hind-cast absolute population sizes from these indices and their relationship to VPAs in later years (Northeast Fisheries Science Center 1997), but the estimates have wide confidence intervals. The Gulf of Maine cod stock apparently produced a succession of strong year classes throughout the 1960s and 1970s, many of which corresponded with those produced by the Browns Bank stock. Georges Bank cod has exhibited large year classes at approximately 5-year intervals, but with a decline in the magnitude of these large year classes over time (Figure 3.1.2). No firm conclusions can be drawn regarding recruitment or recruitment survival in the late 1960s, but it appears that the absolute level of recruitment was very low for the Georges Bank cod stock between 1967 and

Table 3.2.1. MARMAP survey statistics used to estimate cod and haddock larval abundance for the Georges Bank area.

Year	Survey	Middate	Julian day	Interval (days)	Duration (days)
1977	1	18 Feb	49		64
	2	21 Mar	80	31	32
	3	23 Apr	113	33	38
	4	5 Jun	156	43	36
1978	8	2 Mar	62		95
	9	10 May	130	67	74
1979	14	8 Mar	69		85
	15	11 Apr	101	32	35
	16	19 May	139	38	50
1980	21	21 Mar	80		100
	22	1 May	121	41	43
	23	15 Jun	166	45	27
1981	27	1 Mar	60		77
	28	5 Apr	95	35	28
	29	26 Apr	116	21	29
	30	1 Jun	152	36	32
1982	35	3 Mar	62		84
	36	16 Apr	106	44	44
	37	30 May	150	44	44
1983	41	5 Feb	36		67
	42	9 Apr	99	63	62
	43	8 Jun	159	60	41
1984	48	24 Jan	24		60
	49	6 Apr	96	72	59
	50	21 May	141	45	51
1985	57	18 Jan	18		51
	58	24 Mar	83	65	39
	59	6 Apr	96	13	25
	60	14 May	134	38	31
1986	65	28 Jan	28		52
	66	16 Apr	96	68	59
	67	25 May	145	49	59
1987	73	30 Jan	30		68
	74	16 Apr	106	76	45
	75	21 Apr	111	5	21
	76	18 May	138	27	25
	77	9 Jun	160	22	21

1970 (Figure 3.1.2). Likewise Gulf of Maine cod recruitment appears poor between 1965 and 1968. Very good year classes were apparently produced for cod in 1971 in both areas, and in several later years in the 1970s.

Data on the abundance of cod eggs and larvae were collected intensively during 1977–1987 (the MARMAP years; Lough *et al.*, 1994). Survey cruises and durations of sampling are summarised in Table 3.2.1. Annual abundance indices (areal-expanded numbers of animals,

by life stage), expressed as the $\log [n \times 10^9]$ for Georges Bank cod are contoured in Figure 3.2.1. These data are summarised for the period March through May, which is a consistent series constituting the majority of spawning for these stocks. Three egg stages (I, II, III) and four larval stages (3–5 mm, 6–8 mm, 9–11 mm and 12–15 mm) are indexed. The contrast in abundance between 1982 and 1985 was previously reported by Lough *et al.* (1994) who attributed the loss of larvae in 1982 to advection off Georges Bank. Of particular importance is the relatively high abundance of early-stage (3–5 mm)

larvae and eggs in 1980, and 1985 which correspond to the largest cod year classes calculated for Georges Bank cod in the series (Figure 3.1.1).

Correlations among abundance measures for Georges Bank cod eggs, larvae and age-1 VPA estimates for the MARMAP period (1977–1978) are given in Figure 3.2.2 and Table 3.2.2. These data show two important trends: (1) correlations between adjacent life history stages tend to be relatively high, and (2) correlations between early life history stages and VPA recruitment increase progressively from E-I to L3-5 mm, then decline to relatively low levels at later larval stages. The correlation between VPA age 1 recruitment and the abundance of 3–

5 mm is rather high ($r=0.78$; Table 3.2.2), and this observation is consistent with that of Morse (1994). Is this correlation real and why does it apparently break down for larger larvae? It is not possible to conclusively answer these questions, but it can be speculated that poorer correlations for larger larvae may be due to greater potential for gear avoidance or behavioural changes of these animals in relation to smaller larvae. The addition of more years sampling data (which have been collected subsequent to the MARMAP series) would be extremely helpful for resolving the issue of the veracity of this correlation.

Table 3.2.2. Correlation coefficients (r) among loge abundance indices for various egg (E) and larval (L) stages and VPA age 1 numbers for Atlantic cod, Georges Bank stock. Data are for the year 1977–1987 (MARMAP years). Stages are: E1-3 = eggs; L35 = larvae 3 to 5 mm; L68 = larvae 6 to 8 mm; L911 = larvae 9 to 11 mm; L1215 = larvae 12 to 15 mm; VPA1 = vpa age 1 numbers.

Pearson correlation matrix (values ± 0.6 are bolded)

	Ln-E1	Ln-E2	Ln-E3	Ln-L35	Ln-L68	Ln-L911	Ln-L1215	Ln-VPA1
Ln-E1	1.00							
Ln-E2	0.89	1.00						
Ln-E3	0.68	0.92	1.00					
Ln-L35	-0.09	0.27	0.52	1.00				
Ln-L68	-0.43	-0.11	0.16	0.88	1.00			
Ln-L911	-0.17	0.01	0.22	0.81	0.89	1.00		
Ln-L1215	0.74	0.57	0.38	0.12	-0.19	0.32	1.00	
Ln-VPA1	-0.10	0.18	0.35	0.78	0.66	0.54	0.23	1.00

Pairwise frequency table (Numbers of years where log[abundance] data are compared between life stages)

	Ln-E1	Ln-E2	Ln-E3	Ln-L35	Ln-L68	Ln-L911	Ln-L1215	Ln-VPA1
Ln-E1	9							
Ln-E2	9	9						
Ln-E3	9	9	9					
Ln-L35	9	9	9	11				
Ln-L68	9	9	9	11	11			
Ln-L911	9	9	9	11	11	11		
Ln-L1215	8	8	8	10	10	10	10	
Ln-VPA1	9	9	9	11	11	11	10	11

The Georges Bank haddock stock exhibited a very good 1962 (190 million age 1) and record high 1963 (470 million) year class. These year classes were produced during a period of increasing spawning stock biomass (Figure 3.1.4), but nevertheless represented relatively good recruitment survival (Figure 3.1.7). Subsequent to the 1963 year class, recruitment, spawning stock biomass and recruitment survival declined sharply, in the face of extremely intensive exploitation of the stock (NEFSC 1997; Boreman *et al.* 1997). The next large year class was not produced until 1975, which came from low spawning stock biomass, and represented record high recruitment survival (Figure 3.1.7). It has been speculated that, based on heterogeneity in population genetics between the 1975 and 1985 year classes on Georges Bank, that transport from other stock areas may be significant and perhaps implicated (Purcell *et al.* 1996),

although no specific evidence of egg or larval exchange between Georges Bank and other areas has been presented for 1975 or other periods. After 1975, increases in spawning stock biomass resulting from recruitment of age 3 spawners from the 1975 year class, coupled with favourable environmental conditions produced a relatively strong 1978 year class. After 1978, spawning stock biomass fell to record low levels, and recruitment has been at or near historic lows (Figures 3.1.3 and 3.1.4). Both the log(R) and log (R/SSB) time series show some level of temporal autocorrelation (Figures 3.2.5 and 3.2.6), although the strength of the interannual signal is diminished when the data are first-differenced. Recent improvements in spawning stock biomass have come primarily from the moderate-sized 1992 year class, combined with reduced fishing mortality rates on the exploitable stock (Gavaris and Van Eeckhaute

Table 3.2.3. Correlation coefficients (r) among loge abundance indices for various egg (E) and larval (L) stages and VPA age 1 numbers for Haddock, Georges Bank stock. Data are for the year 1977–1987 (MARMAP years). Stages are: E1-3 = eggs; L35 = larvae 3 to 5 mm; L68 = larvae 6 to 8 mm; L911 = larvae 9 to 11 mm; L1215 = larvae 12 to 15 mm; VPA1 = vpa age 1 numbers.

Pearson correlation matrix (values ± 0.6 are bolded)

	Ln-E1	Ln-E2	Ln-E3	Ln-L35	Ln-L68	Ln-L911	Ln-L1215	Ln-VPA1
Ln-E1	1.00							
Ln-E2	0.87	1.00						
Ln-E3	0.60	0.86	1.00					
Ln-L35	0.39	0.71	0.91	1.00				
Ln-L68	0.42	0.71	0.73	0.51	1.00			
Ln-L911	0.51	0.43	0.23	-0.26	0.93	1.00		
Ln-L1215	0.60	0.54	0.23	0.25	0.41	0.46	1.00	
Ln-VPA1	0.01	0.14	0.11	0.35	-0.02	0.11	0.61	1.00

Pairwise frequency table (Numbers of years where log[abundance] data are compared between life stages)

	Ln-E1	Ln-E2	Ln-E3	Ln-L35	Ln-L68	Ln-L911	Ln-L1215	Ln-VPA1
Ln-E1	9							
Ln-E2	9	9						
Ln-E3	9	9	9					
Ln-L35	9	9	9	11				
Ln-L68	9	9	9	11	11			
Ln-L911	8	8	8	9	9	9		
Ln-L1215	8	8	8	9	9	9	9	
Ln-VPA1	9	9	9	11	11	9	9	11

1997; NEFSC 1997). Recruitment survival is now near the long-term median, implying that if spawning stock biomass was larger, recruitment would increase as well (Figure 3.1.7).

Data on the abundance of Georges Bank haddock eggs and larvae from the MARMAP series are presented in Figures 3.2.3 and 3.2.4 and Table 3.2.3. Late-stage larvae (12–15 mm) were the most abundant in 1978, which corresponds to the largest year class produced in the MARMAP years (Table 1.3.3). Abundance of late-staged larvae was lowest in 1982 and 1986, which were among the smallest year classes produced in the series. As with cod, correlations were highest among adjacent life history stages (Table 3.2.3). Unlike cod, however, the best overall predictor of VPA age-1 abundance is the abundance of 12–15 mm larvae.

The dramatic decline in haddock recruitment in the mid-1960s occurred during a relatively cold period, as described in Section 2. These cold temperatures also led to changes in the distributions of some fish species, although responses of cod and haddock were modest in comparisons with pelagic species (Mountain and Murawski 1992; Murawski 1993). Haddock generally accommodated the colder temperatures by moving to slightly deeper water, although only about half of the temperature change could be accommodated in this manner (Mountain and Murawski 1992). Significant changes in the density distribution of demersal juvenile and adult cod and haddock, particularly on Georges Bank have occurred over time (Figures 3.2.7 and 3.2.8),

primarily as a result of intensive harvest and reduced recruitment. For both species, the distributions now appear more confined to the Northeast Peak and Great South Channel areas than in previous years. Obviously this has some implication for the spatial distribution of spawning products. Walford (1938) showed several areas of high concentration of haddock eggs (Great South Channel, Northeast Peak) in 1931 and 1932. Recent ichthyoplankton work had indicated relative few eggs produced from the Channel area, which may have been a more important contributor to Georges Bank haddock year class strength in former years.

For both cod and haddock, stock recruitment relationships are noisy (NEFSC 1997), but there is a reduced probability that moderate-strong year classes will be produced, when SSB is low (Overholtz *et al.*, 1986). Overfishing of these resources is thus implicated as a primary factor in reduced recruitment in recent years (Sinclair and Murawski 1997). Recruitment survival has improved recently for Georges Bank haddock, while decreasing for Georges Bank and Gulf of Maine cod. Recent changes in recruitment survival enhance the prospects for stock recovery of Georges Bank haddock, while exacerbating the effects of overfishing in the case of Gulf of Maine cod (NEFSC 1997).

One aspect of historic overfishing of these stocks that must be considered is the effects of reduction in the age at first spawning, and increasing reliance on first- and second-time spawners as contributors to SSB (Hunt 1996; O'Brien *et al.*, 1993; NEFSC 1997; Murawski *et*

al., 1999). If eggs and larvae produced by young (small) adults have poorer survivorship, then this may be a significant contributing factor to observed declines in recruitment and recruitment survival (Trippel 1995; Chambers and Trippel 1997).

In general, previous attempts to correlate recruitment strength to environmental variation for Georges Bank and Gulf of Maine cod and haddock have resulted in weak or non-existent relationships. The addition of new physical data (Section 2), combined with appropriate transformations of stock-recruitment information, and the availability of circulation models that can be run in a retrospective mode make it an appropriate time to re-investigate these relationships. In particular, a number of important hypotheses concerning the Georges Bank and Gulf of Maine cod and haddock stocks bear in-depth investigation:

Is there any indication from physical data or sampling of early life history stages, of transport of haddock to Georges Bank in 1962, 1963 or 1975?

What is the significance of haddock and cod spawning in the Great South Channel to overall recruitment of the Georges Bank cod and haddock stocks (this issue is particularly timely, given the year-round closure of two large areas on the USA side of the Bank)?

Correlation studies have shown coherent fluctuations between Browns Bank cod and Gulf of Maine cod. Is transport among these stocks likely to be a significant factor in recruitment variation?

What is the relationship between egg and larval survival and the age, length and reproductive experience of spawners?

Did cold water conditions in the 1960s result in changes in development and growth rates of eggs and larvae?

Can egg and larval data collected in the post-MARMAP years be used to better define the relationship between egg and larval abundance and year class size?

Can the distribution of eggs and larvae be predicted from the distribution of adult cod and haddock as inferred from groundfish surveys?

3.3 Environmental influences on cod and haddock stock productivity on the Scotian Shelf during the past 50 years

K. Frank, B. Petrie, and K. Drinkwater

Exploratory analyses were carried out to investigate the possible influence of several environmental variables on the recruitment and survival (ratio of recruitment to spawning stock biomass) of cod and haddock on the Scotian Shelf. The stocks examined included the NAFO

Div. 4X and Div. 4VW haddock stocks and the Div. 4X and Div. 4VsW cod stocks. In addition, evidence for dependence of recruitment of spawning stock was evaluated for each of the stocks. Only Div. 4VsW cod had a significant stock-recruitment relationship and for this stock residuals from this relationship were evaluated in relation to the physical variables. The physical variables included temperature, stratification (density difference between the surface and 50 m) on Misaine, Western, Emerald, and the Browns Bank region, positions of the shelf/slope front and the Gulf Stream, the North Atlantic Oscillation (NAO) index, the river discharge from the Gulf of St. Lawrence (RIVSUM), sea level at Halifax and the along and across-shore wind stresses at Sable Island and near Georges Bank; chemical variables included oxygen and nutrients; and biological variables included estimates of abundance of *Calanus* stages I-IV and V-VI, *Paracalanus* and *Pseudocalanus* plus the colour index from the continuous Plankton recorder (CPR) from the eastern and western Scotian Shelf.

All of the correlations between *Calanus* stages I-IV and recruitment/survival for the four stocks were negative and the maximum correlation was seen in the 4VsW cod recruitment residual from the stock and recruitment relationship (Figure 3.3). Analysis of the relationship between both larger (*Calanus* stage V-VI) and smaller (*Paracalanus/Pseudocalanus*) size groups of zooplankton and recruitment/survival also resulted in negative correlations but were of consistently smaller magnitude than the correlations with *Calanus* stage I-IV. The magnitude of the correlations between the colour index and recruitment/survival was low and the sign of the correlation was both positive and negative depending on the stock examined. Nutrients were positively correlated with all four stocks while oxygen was generally negatively correlated with recruitment/survival. The negative correlation with oxygen was not unexpected given that nutrients and oxygen tend to be inversely correlated. The correlations between adjusted sea level at Halifax and recruitment/survival for all of the stocks was negative and of low magnitude.

Correlations between water temperature at 75 and 100 m and recruitment/survival were generally positive but of low magnitude. This result is consistent with the observation that higher temperatures generally promote increased recruitment and better survival. Weaker stratification typically resulted in higher recruitment with the highest correlations found for 4VsW cod. Survival was also higher, in general, when stratification was weaker although the highest correlation between the density gradient and survival was positive between 4VsW cod and Emerald/Western density gradients. The positions of the Gulf Stream and Shelf/Slope front show weak negative correlations with recruitment and survival. There is relatively high correlation between the two indices with the correlation between annual values being 0.70. The negative correlation with recruitment and survival indicates that when the Shelf/Slope front and Gulf Stream are closer inshore recruitment is poorer. This result is similar to the conclusions of Myers and

Drinkwater (1989) who demonstrated that greater ring activity was associated with the Shelf/Slope front being closer inshore. Thus we interpret the negative relationship between recruitment and survival acting through displacement (entrainment) of the early life stages from the offshore banks. The negative correlation with recruitment and the NAO index was puzzling and a search for a mechanism was not pursued. Correlations with RIVSUM and the wind stresses and recruitment/survival were generally very weak - a result consistent with previous findings of Myers and Drinkwater and (1988/1989). Multiple regressions of survival against *Calanus* and environmental variables were also examined and, in general, accounted for approximately 50% of the variance in survival. In conclusion, the analyses conducted represents work in progress and further research is planned. Questions such as whether strong correlations existed between specific environmental variables and recruitment/survival indices and then degraded was not addressed. Characterisation of the environmental conditions associated with strong and weak year classes or periods of high and low survival were also not evaluated.

3.4 Recruitment patterns of cod and haddock in the North Atlantic

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We examined recruitment patterns of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) from eight regions in the North Atlantic. We selected regions for comparison based on the availability of contemporaneous estimates of stock and recruitment for both species within a region. We considered only information derived from sequential population analysis to eliminate differences due to analytical methods of estimation. The regions considered were Georges Bank, Browns Bank, the Eastern Scotian Shelf, the Faroe Plateau, Iceland, the Barents Sea, the North Sea, and the West of Scotland. We considered the following metrics: recruitment variability (measured as absolute numbers at age 1 and as deviations from a fitted stock-recruitment curve - Figure 3.4.1), the rate of recruitment at low spawning stock sizes (a measure of resilience of the stock to exploitation), the skewness in recruitment, and autocorrelation in recruitment for both species within regions. We also examined synchrony in cod and haddock recruitment within regions.

We found highly significant differences in recruitment variability and resilience between cod and haddock in paired comparison tests. No significant differences in the skewness in recruitment were found. Haddock consistently exhibited higher levels of recruitment variability and lower levels of resilience than cod (Figure 3.4.2). Autocorrelation in recruitment was related within regions for cod and haddock, possibly indicating serial correlation in forcing mechanisms within regions

affecting cod and haddock (Figure 3.4.3). Alternatively, estimation errors in age determination may underlie the apparent patterns correlation in successive year classes. Life history characteristics that can lead to higher resilience in cod include lower pre-recruit mortality levels. Factors potentially contributing to lower levels of recruitment variability in cod include stronger compensatory mechanisms during the pre-recruit stage, a longer seasonal reproductive period and risk-spreading reproductive strategies, and lower susceptibility to variability in food supply.

Cod and haddock exhibited moderate synchrony in recruitment patterns within regions. In six out of the eight regions, the correlation between recruitment (adjusted for spawning stock size) for cod and haddock was ~ 0.5, indicating moderate levels of synchrony in recruitment within regions (Figure 3.4.4). This result suggests that although some dominant environmental forcing mechanism(s) may be affecting recruitment of these species within regions, substantial unexplained variability in recruitment remains. Subtle differences in the timing and location of spawning of these species within regions in relation to events in the physical and biological environment presumably accounts for the differences in relative recruitment within regions. Synchrony in recruitment within species was evident in the Northwest Atlantic, particularly between Georges and Browns Banks. Evidence for within-species synchrony in the Northeast Atlantic was less clear. Consideration of overall patterns of recruitment within and between species and regions suggests that no single, dominant environmental factor is likely to emerge as an explanation for observed patterns of recruitment of cod and haddock in the North Atlantic.

3.5 Cod and haddock spawning on Georges Bank in relation to water residence times

F. H. Page¹, M. Sinclair², C. E. Naimie³, J. W. Loder, R. K. Losier¹, P. L. Berrien⁴, and R. G. Lough⁵

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The seasonal and geographic patterns of spawning for Georges Bank cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) are estimates using composite distributions of stage I eggs derived from the Marine Resources Assessment and Prediction (MARMAP) data set (1977 to 1987). The inferred mean spawning locations are compared with patterns in particle residence times derived from a three dimensional prognostic circulation model that estimates the tidal and

seasonal mean circulation. The comparisons indicate that cod and haddock spawning occurs at times and locations characterised by model residence times in excess of 35 days. Changes in residence time in past decades could have influenced the retentiveness of the bank and thus mean recruitment levels. Studies on hydrographic conditions during contrasting warm/cold periods will be used to model the potential impacts of circulation changes on cod and haddock egg and larval residence times. The results are discussed in the context of fish population regulation theory, particularly the member/vagrant hypothesis and the concept of abundance-dependent vagrancy.

3.6 Larval retention on Georges Bank and good year classes: the MARMAP years 1977-1987

R. G. Lough and P. L. Berrien

Is the size of the year class related to the retention of larvae on Georges Bank? This hypothesis is explored through an examination of the MARMAP 11-year time series of cod and haddock egg/larval distributions during 1977-1987. For each winter/spring period, total abundance estimates were made for three egg and four larval size classes, and average seasonal loss rates were compared with known environmental events and size of the recruited year class. Sub-area abundances were also estimated for the larval stages during the spring of each of the years to assess the absolute and relative retention of larvae on the Bank shoaler than 70 m. Consistency in the relative rankings of cod and haddock larvae retained on the Bank indicate an underlying physical process; however, highly retentive years are not always associated with strong years of recruitment. Four candidate years (1978, 1979, 1980 and 1984) are described for future 3-D modelling based on available data.

The spring of 1978 is suggested because it had the highest year class of recruited haddock in the MARMAP time series, and it could serve as a proxy for the extremely high 1963 haddock year class when there is no available ichthyoplankton data. Cod recruitment was moderately high in 1978. There is good environmental/hydrographic data for spring 1978 on Georges Bank, but only two larval surveys.

The 1979 year is suggested because it has the best coverage of environmental/hydrographic data for Georges Bank, Gulf of Maine and SW Nova Scotia for spring, summer and fall. It is also the best year for merging MARMAP and SSIP zooplankton surveys to study the zooplankton supply from Scotian Shelf to SW Nova Scotia and Georges Bank. Ichthyoplankton survey coverage was also good on Georges Bank in 1979; a survey occurred during the months of March, April and May, and haddock larvae were abundant.

The 1980 year is suggested because it was a large year class for cod and also appears to be a good year for retention of larvae on the Bank. The other strong year class of cod was 1985. Advection of larvae on Georges

Bank during 1985 was simulated in a 3-D circulation model using mean monthly winds and results were reported in Lough *et al.* (1994).

Finally, the 1984 spring season is suggested for comparison with other years because it was a year that resulted in low recruitment of both cod and haddock on Georges Bank and Scotian Shelf.

3.7 Gulf of Maine and Georges Bank zooplankton retrospective from CPR and MARMAP surveys

J. W. Jossi, J. R. Goulet, J. R. Green, and J. Kane

An examination of the past several decades of zooplankton variations in the Gulf of Maine and on Georges Bank was conducted based on data from the MARMAP and Ships-of-Opportunity (SOOP) surveys. The zooplankton selected for the examination were based on contents of larval cod stomachs for which consistent zooplankton series existed. The examination was quite preliminary, but although minor biases remain in the results, some persistent, major differences in the seasonality and year-to-year abundances can be seen in both the Gulf of Maine and Georges Bank data. In the Gulf of Maine earlier studies (Jossi and Goulet 1993) show the periods 1965-1975 and 1983-1985 to be low years for plankton abundance, while 1961-1964 and 1976-1982 were high years. The current examination adds the period 1990-1997 to the list of high years. Although varying somewhat in magnitude *Calanus finmarchicus*, c1-4; *Copepoda*, *nauplii*; and total *Copepoda*, all stages; follow this pattern (Figures 3.7.1-3.7.3). In addition, their variations show a change in seasonality beginning about 1990 wherein the annual period of high abundance is extended later into the summer, and, in the case of total *Copepoda*, extended to near the end of the year.

The data for Georges Bank is confined to the "spring" months of roughly mid/late - February to mid-May. The 1983-1985 low years for the Gulf of Maine are also seen here for zooplankton biomass (Figure 3.7.4), and for the copepods, *Oithona* spp., *Paracalanus parvus*, *Pseudocalanus minutus*, *Metridia lucens*, and *Centropages typicus*. Higher than average abundances for the period since 1990 can be seen for *Oithona* spp., *Temora longicornis*, *Centropages typicus*, and *Metridia lucens* (Figure 3.7.5). These taxa were among the twelve most ubiquitous taxa on Georges Bank during the MARMAP "decade" (1977-1987). The data bases from these two surveys contain information of higher temporal resolution than has been examined here. Given time windows more appropriate to feeding requirements of early stage cod, decadal series of zooplankton could be refined and made more relevant. However, the low abundance period of 1983-1985, and the changing seasonality since 1990 are expected to persist in most subsequent analyses.

3.8 Decadal changes in the color index and selected zooplankton taxa indices on the Scotian Shelf

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Continuous Plankton Recorder data for phytoplankton colour index, total diatoms, *C. finmarchicus* stages 1–4, *C. glacialis*, *C. hyperboreus* and *Paracalanus*–*Pseudocalanus* collected between the years 1961 and 1994 in the Canadian Atlantic region were analysed for geographic and temporal changes (Figure 3.8.1). Significant differences on both geographic and temporal scales were detected. Changes were observed in these taxa after 1991 with the colour index increasing significantly and a shift in the climatology occurring as concentrations became significantly higher in the first three months of the year compared to the years 1961 to 1976. A seasonal decomposition analysis on data of consecutive monthly means for the years 1961–1994 showed a cyclic pattern in the abundance of *C. finmarchicus* stages 1–4 (Figure 3.8.2).

3.9 A regime shift in the Northwest Atlantic? An analysis of copepod species dominance variability in relation to the North Atlantic oscillation

Marjorie C. Lambert

One of the possible factors influencing the inter-annual variability of fish stocks and zooplankton abundance is climate. It has been theorized that a mismatch between the time of fish spawning (release of larvae) and the peak abundance of zooplankton prey may be the main cause of recruitment failure (Cushing 1975; 1982). One of the possibilities influencing this inter-annual variability is the North Atlantic Oscillation (NAO). The NAO is a climatic phenomenon caused by fluctuating high and low sea level pressures in the North Atlantic between Iceland and the Azores. It has been theorized that the extreme sea level pressure anomalies influence sea surface temperatures in the North Atlantic which may effect the timing of the phytoplankton spring bloom (Fromentin and Planque 1996). The NAO winter climate regime may have significant influence on the Gulf of Maine's environment and biology. When the winter NAO is in an extreme positive state (83) (Figure 3.9) westerly wind stress over the northeast Atlantic intensifies, the sea surface conditions become more turbulent and temperature increases (Planque and Fromentin 1996, Hurrell 1996). An inverse relationship between *C. finmarchicus* and sea surface temperature has been well documented (Davis 1982; Meise-Munns *et al.*, 1990; Carlotti *et al.* 1993, Planque and Fromentin 1996). The

positive relationship between *C. typicus* and sea surface temperature was also observed by Meise-Munns (1990) in the western portion of the GOM during the same time 1977–1987. The GOM winter estimates of wind speed and direction explained a significant amount of variability in the NAO winter index. Therefore these variables may be used as a proxy for stress (turbulence) on the sea surface and may explain why the CPR (surface) estimates of *Calanus* spp. C.1–4 dominance provides more significant results in comparison to the bongo net (at depth) estimates of *C. finmarchicus* dominance. *C. finmarchicus* is most abundant during the spring when surface waters are relatively cool and well mixed. In contrast, *C. typicus* is most abundant during the autumn season when surface waters are highly stratified and are at peak annual temperatures. Given the contrasting scenarios among these two copepod species is it possible that 1) anomalously warm winter surface temperatures, possibly influenced by a north Atlantic-wide climate regime that may be more conducive to *C. typicus* biology, can result in a poor production cycle for the following spring generation of *C. finmarchicus* or 2) an influential mechanism caused by the NAO may be occurring at depth thereby affecting the inflow of water from the Scotian Shelf, thermal stratification, and convective processes. Future research efforts will attempt to address these questions as well as focusing in on a longer time series of the GOM environment and *C. typicus* abundance estimates, and the connectivity (lag ?) between the northeast and northwest fluctuating SLP anomalies and westerly winds.

3.10 Multiyear variability in high frequency forcing of plankton variability on Georges Bank

B. J. Rothschild, A. Gangopadhyay, and H. S. Kim

An examination of near-surface water temperature at the Georges Bank meteorological buoy reveals diurnal and semi-diurnal variability at tidal frequencies. There is considerable inter-annual variability in the temperature signal. For example, the temperature series for the Spring of 1987 were particularly marked with unusually high variability and seemingly lower frequency events. In order to study the effect of the temperature signal, we studied the relationship between surface temperature and the inferred abundance of *Calanus* at approximately 600 MARMAP stations selected because of their proximity to the Georges Bank meteorological buoy. The low frequency annual and seasonal signal components were removed from the data leaving warmer than average and cooler than average hourly residuals. The abundance of *Calanus* was significantly greater at stations represented by cool residuals. The data imply that intrusions of shelf water onto the bank contained significantly less *Calanus* than the Georges Bank water. These observations suggested that high frequency forcing may play an important role in the estimation of Georges Bank plankton abundance. The data also suggest that estimates of the advection of fish larvae on and off the bank may be influenced by the high frequency forcing.

3.11 Predation processes

Michael J. Fogarty and Larry Madin

Predation has long been recognised as a critical factor affecting survivorship during the pre-recruit phase of marine fish. Recent studies under the US GLOBEC and NOAA Coastal Ocean Programs have sought to determine the role of invertebrate and fish predators, respectively, in Georges Bank ecosystem dynamics. These studies have documented the potential importance of predation processes on the early life stages of cod and haddock and *Calanus finmarchicus* and *Pseudocalanus* spp. Interaction with physical environmental factors can play a critical role in determining predation impacts.

US GLOBEC studies have focused on known invertebrate predators of fish larvae and copepods and have identified a potentially important species that had not been previously linked to predation in pelagic food webs on Georges Bank. GLOBEC studies have shown episodic high concentrations of the typically sessile hydroid, *Clytia* spp. in the water column on the bank. The hydroids are found in highest concentrations at depth and on the central plateau of the bank where resuspension rates and mixing are strongest. Laboratory feeding experiments demonstrate that the hydroids can capture and consume both fish larvae and copepods. Factors affecting the detachment and suspension of the hydranths in the water column have not been conclusively identified but storm events have been suggested as a potential natural mechanism. Factors affecting storm frequency, strength, and endurance may therefore interact with the dynamics of hydroid populations to determine the probability of encounter between these predators and fish larvae and copepods. Factors affecting mixing rates in general will also influence the probability of encounter.

NOAA Coastal Ocean Program studies of predation processes on Georges Bank have focused on the role of piscivorous fish in controlling the structure of fish communities. Estimates of coastwide populations of Atlantic herring and mackerel indicate that abundance of these species is currently at the highest levels recorded during the last three decades. Both species are known to consume the early life stages of fish as well as mix of zooplankton species. Cod and haddock have been identified in the stomachs of herring and mackerel in NCOP cruises on Georges Bank although these species generally comprise less than one percent of the diet (wet weight) of the small pelagics. The high abundance levels of the pelagics (estimated to be in excess of 5 million metric tons of adult herring and mackerel) does indicate, however, that the impact on gadoid eggs and larvae can be substantial. Mackerel appear to concentrate in preferred temperature strata during the northward migration from the overwintering grounds in the Mid-Atlantic Bight. Interannual variability in temperature may therefore affect the timing and position of the migrating mackerel and influence the probability of

encounter between mackerel schools and patches of gadoid eggs and larvae. In some years, mackerel may not remain on the shelf in response to temperature patterns but rather may concentrate in the slope water environment.

These studies collectively indicate that we should consider interactive effects of the physical environment and predation processes in considering how climate-scale events might influence the dynamics of gadoids on Georges Bank.

3.12 Reconstructing lifetime temperature histories of cod from otolith oxygen isotope compositions

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Oxygen isotope (^{18}O) methods have been applied to the otoliths of many fish species over the past thirty years. The consensus of these earlier studies is that the ^{18}O of teleost (bony fish) otoliths, which are composed of aragonite, are usually in isotopic equilibrium with ambient conditions (^{18}O of seawater, temperature) and therefore provide a potential method for environmental reconstruction. However, results from earlier calibration studies show a large amount of scatter ($\pm 2\%$ for a given temperature equivalent to an uncertainty of 8°C for a given ^{18}O value (Kalish 1991a; b). This leaves room for an interpretation of possible disequilibrium, which then would limit the reliability of this method. In addition, previous studies do not provide high-resolution time-series, as either entire otoliths were used for single analyses or the sample resolution was quite coarse owing to physical constraints of conventional technology.

In this study, detailed ^{18}O records were obtained from cod otoliths, using new micro-sampling methods that allow for high temporal resolution within the otoliths' seasonal growth bands (up to 20 plus samples/yr). A dozen otoliths were sampled from specimens of varied age (2 to 12 years), collected from different locations in the eastern North Atlantic, including: 1) the Faroes, 2) Irish Sea, 3) southern North Sea, 4) northern North Sea, 5) Barents Sea, and 6) MRI Aquarium, Bergen Norway. The seasonal ^{18}O signals obtained from the cod otoliths generally coincide with the otoliths' visible growth bands, supporting independent growth band-count age estimates. As an environmental indicator, otolith ^{18}O records show a close correspondence to the expected signal based on the bottom temperature characteristics (annual mean, maximum, minimum and range) of their respective capture regions (Figures 3.12.1 and 3.12.2). Based on these results we conclude that cod otoliths are deposited in oxygen isotopic equilibrium with ambient conditions, are an accurate ($\text{SE } 1.0^\circ\text{C}$) recorder of

surrounding temperature fields, and consequently can be used to reconstruct lifetime temperature histories.

3.13 Summary

3.13.1 Factors related to cod and haddock recruitment variation

Dominant year classes of Atlantic cod were apparently produced on Georges Bank in 1966, 1971, and assuredly in 1980, 1983 and 1985 (underlining indicates unusually large cohorts in VPA time-series). In the Gulf of Maine, large year classes were probably produced in 1971, 1973, 1977, 1979, 1983, and assuredly in 1987. On Browns Bank, dominant cod year classes occurred in 1959, 1962–1963, 1977–1978, 1985, 1987 and 1992, while on the E. Scotian Shelf, the largest year classes were 1961–1964, 1980, 1986 and 1987.

Recruitment survival ($\log[R/SSB]$) for Georges Bank cod was greatest in 1966, 1971, 1975, 1980 and 1985; in the Gulf of Maine cod recruitment survival peaked in 1971, 1973, 1977, 1986 1987 and 1993. Recruitment survival was greatest for Browns Bank cod in 1959, 1963, 1972–1975, 1985, 1987 and 1992, and on the E. Scotian Shelf, cod survival was best in 1974, 1977, 1993 and 1994.

There is a moderate degree of concordance in annual landings, recruitment and recruitment survival among the various cod stocks, with the highest degree of correlation in recruitment and survival between adjacent stock pairs in the southern extent of the area (e.g., Gulf of Maine and Browns Bank, Georges Bank and Browns Bank and Gulf of Maine and Georges Bank).

The significance and degree of cross-correlation of cod recruitment and survival was examined in more detail at various time lags for several stock pairs, using $\log(R)$ and $\log(R/SSB)$ (Tables 1.3.5 and 1.3.6). For Gulf of Maine vs. Browns Bank cod, there was a significant positive correlation in recruitment and survival at lag 0 when data were 1st-differenced (Figures 3.13.1 and 3.13.2). For Georges Bank vs. Browns Bank cod, correlations between recruitment survival were not significant at any lags (Figure 3.13.3).

The high degree of correspondence in annual recruitment/survival between Gulf of Maine and 4X cod stocks, combined with numerical simulations showing egg and larval drift among the spawning areas (Section 2.3), supports the possibility that transport takes place between them. Studies based on the FEP cruises in 1983–1985 (which are reported in the Canadian Journal of Fisheries and Aquatic Sciences 46(4) 1989 and Supplement 1) and distributions of eggs and larvae during SSIP cruises in 1979–1981 (e.g., Brander and Hurley, 1992) provide additional evidence.

Trends in low-frequency variation in cod survival showed no obvious correlations among areas (Figure 3.1.6). There was a reduction in recruitment survival in

the late 1960s on Browns Bank, but no corresponding relationship was apparent in the other cod stocks. In all areas, recruitment survival improved in the 1970s, and on Browns Bank and E. Scotian Shelf, declined in the 1980s. Low-frequency signals in cod recruitment survival indicate a reduction in the three southern stocks in the 1980s, and an increase in the 1990s.

Analyses of abundance of Georges Bank cod eggs and larvae, and age-1 recruitment estimates from VPA, showed highest correlations between adjacent life history stages. The best predictor of abundance at age 1 was the abundance of 3–5 mm larvae. This result, if true, has important implications for the design of future research programs on factors influencing recruitment (i.e., if recruitment strength is set as young [small] larvae, then understanding processes influencing egg survival and first feeding of larvae becomes relatively more important).

Dominant haddock year classes occurred on Georges Bank in 1962–1963, 1975 and 1978. On Browns Bank, large cohorts were spawned in 1962, 1963, 1975, 1981, 1993 and 1994, while on the E. Scotian Shelf, dominant year classes were 1952, 1963, 1980–1982, and 1988.

Recruitment survival of haddock on Georges Bank peaked in 1962, 1963, 1975, 1978, 1992 and 1993. Browns Bank haddock recruitment survival was greatest in 1963, 1988, and 1993–94. On the E. Scotian Shelf, survival was highest in 1963–1964, 1975–1977, 1988 and 1993.

There was a moderate degree of concordance in landings, recruitment and recruitment survival among adjacent pairs of haddock stocks. $\log(R)$ and $\log(R/SSB)$ were positively correlated between the Georges Bank and Browns Bank haddock stocks at lags of 0 (same year) and -3, when the data were 1st-differenced (Figures 3.13.4 and 3.13.5).

Although there is no direct evidence for exchanges of haddock eggs, larvae or juveniles among stocks, the very strong 1962 and 1963 year classes in all areas at least argues for a common environmental factor that contributed to excellent recruitment survival in those two years. Spawning populations responsible for those two large year classes were large and exploited at moderate rates prior to the build-up in distant-water fleet effort.

The outstanding recruitment/survival associated with the 1975 haddock year class on Georges Bank may have partially resulted from eggs or larvae transferred from Browns Bank, although no evidence of such transport has been presented. Differing genotypes of fish sampled from the 1975 and 1985 cohorts on Georges Bank support an hypothesis of interchange with other haddock genomes.

As with cod, correlations among abundance measures for haddock egg and larval stages and age-1 VPA estimates are highest for adjacent stages. Correlations of egg and larval indices were different than corresponding

relationships for cod; the best predictor of haddock year class size was the abundance of 12–15 mm larvae.

In only one case was there a substantial correlation between cod and haddock recruitment or recruitment survival within a stock area (E. Scotian Shelf), and in that case, $\log(R/SSB)$ was not significantly cross-correlated at any lag, when the data were 1st-differenced (Figure 3.13.6).

The decline in recruitment survival of all haddock stocks in the mid- to late 1960s generally corresponds to a reduction in shelf temperatures, increase in southwestward transport along the shelf break, and a reduction in the low-frequency signal in the NAO index (Figure 3.13.7). As noted in Section 2, a below-average NAO index is associated with higher storm frequencies in this region, which, depending on wind direction, may result in greater advective losses. Improvements in recruitment survival in the 1970s roughly corresponded to an increase in temperatures and the NAO index. However, the relative magnitudes of post-1960s changes in the low-frequency signals in recruitment survival and NAO indices differ, and declines in survival in the 1980s (e.g., on Browns Bank and the E. Scotian Shelf) are not well correlated to the NAO.

Correlations of cod and haddock recruitment and recruitment survival with various individual environmental indices produced weak to moderate positive and negative relationships. For the Scotian Shelf and Browns Bank stocks, there were inverse correlations between recruitment and zooplankton abundance (Figure 3.3); recruitment survival was weakly correlated with indices of phytoplankton production; nutrients were positively correlated and oxygen negatively correlated with survival. Correlations between water temperature and recruitment/survival were positive but of low magnitude. Multiple regressions of *Calanus* abundance and environmental indices accounted for about 50% of the variance in recruitment survival. Many reported correlations have subsequently changed as more data are added. This is often due to incompleteness of the initial model, and more detailed understanding of the processes involved is needed. Exploratory correlations are useful in indicating which variables and processes are likely to be important.

Trends in zooplankton abundance, and especially that of *Calanus*, in the Gulf of Maine-Browns Bank region are in general correspondence with low-frequency variation in recruitment survival for Browns Bank cod and haddock, and Georges Bank haddock (declines in the mid-1960s to mid-1970s, followed by improvement until 1983–1985, and higher abundance in the current period, Figure 3.7.1). The abundance of dominant copepod species is related to seasonal water temperature patterns and wind stress (turbulence, as indexed by the NAO and winter wind speed/direction), with the distribution of *C. finmarchicus* strongly negatively related to temperature when/where the water was stratified (Meise and O'Reilly 1996).

Zooplankton data from the Scotian Shelf indicate substantial cyclic variation in *Calanus* production over time, with the highest abundances in 1964–1965 and 1968–1969. The total colour index increased significantly in the 1990s, and particularly in the first three months of the year.

Research has been initiated on the importance of hydrographic retention areas for eggs and larvae as determinants of year class strength. Initial simulations indicate that haddock and cod spawning typically occurs in areas of Georges Bank with residence times in excess of 35 days. Analysis of the spatial distribution of cod and haddock spawning and spawning products in relation to interannual variation in water residence times will allow an evaluation of the potential importance of advective losses, but information on survival rates within and outside the “retention area” is also required.

On a larger scale, cod and haddock exhibited moderate synchrony within eight regions of the North Atlantic. Haddock were consistently more variable in recruitment, and thus less resilient than cod. The reasons for cod's greater apparent resilience are unclear but may relate to its purported longer seasonal reproductive period, to other ‘risk-spreading’ reproductive strategies, and perhaps lower susceptibility to variations in food supply. Morse (1994) estimates the standard deviation of the normal distribution of numbers of cod larvae on Georges Bank to be only 17 days. This suggests that the spawning period for cod is no longer on Georges Bank than it is in other areas where such estimates exist e.g. around the British Isles (Brander 1994). Variation in spawning time in haddock has not been computed in the same way as for cod.

The abundance of potential fish predators of Georges Bank cod and haddock larvae (primarily small pelagic fish including herring and mackerel) has increased significantly since the early 1980s, but the impact of these predators on larval mortality has not been quantified. Recent trends in recruitment survival of Georges Bank haddock and cod do not appear correlated with mackerel and herring abundance. Potentially high rates of predation by invertebrate species (e.g., hydroids) on cod and haddock larvae may occur if these species are abundant in larval retention areas.

Variations in surface and bottom water temperatures may influence the co-occurrence of fish predators and egg/larval prey (warmer temperatures favour earlier spring migrations of herring and mackerel over Georges Bank). However, the significance of variability in the co-occurrence of prey and predators due to changes in water temperatures has not been evaluated.

Likewise, rates of development of various egg and larval stages are temperature dependent (Bennet 1939; Walford 1938; Lawrence 1978). Whether, as a consequence, there is a link between recruitment survival and water temperature, awaits more detailed analyses of the distribution, abundance and survival of these life history stages, in relation to spatially explicit temperature fields.

Intensive exploitation of all the stocks, and particularly haddock, resulted in rapid and substantial reductions in SSB in the mid- late-1960s. All haddock stocks reached historic lows in SSB during the early- mid-1970s. Based on evidence currently available, it is not possible to ascribe reductions in survival of early life stages of haddock during the late 1960s to environmental or demographic origin. The very high rates of haddock removals during this period resulted in rapid declines in abundance and proportions of older spawners in the populations, and possibly changes in the distributions of spawners and spawning products.

No single environmental factor yet considered appears to have a dominant influence on the recruitment and recruitment survival of Georges Bank stocks. This view is supported by: (1) Walford's (1938) work showing that relatively strong year classes (50 million age-1 haddock) could emerge from very different environmental scenarios (1931 and 1932), (2) the lack of a strong, temporally-stable, correlation between environmental indices (e.g., temperature, wind stress, salinity, transport, etc.) and recruitment, despite a significant amount of searching for simple correlations, (3) the modest level of synchrony in cod and haddock recruitment/survival within an area (thus implying that influential environmental factors are different between species that spawn at approximately the same time, and in similar locations, and that the effects must therefore be subtle), (4) the observations in 1932 and 1987 that, despite significant westward transport of haddock larvae off Georges Bank, high levels of recruitment could occur, and (5) the observation that at moderate to high levels of SSB, the probability of producing a good to excellent year class is higher than if SSB is relatively low (Overholtz *et al.*, 1986; NEFSC 1997).

When SSBs were larger, and spawning was by many age groups, adults (Figure 3.2.7 and 3.2.8) and egg production were apparently distributed over a wider area of Georges Bank, than when stocks were low. If there are multiple environmental hazards to eggs and larvae operating at differing temporal and spatial scales, then evolution favours a strategy of distributing spawning products over a variety of habitats, and widening the production curve over time. In such a scenario, moderate to good recruitments could be produced even if a significant fraction of the eggs or larvae in a particular area are lost through variable oceanographic processes, lack of proper food, or were preyed upon. The effect of this "don't place all your eggs in one basket" strategy might very well appear as an increasing probability of moderate-good year classes with increasing SSB (consistent with empirical observation).

3.13.2 General research issues

High-frequency variations in copepod abundance and water temperature on the southern flank of Georges Bank imply that slope water intrusions contain less *Calanus* prey than Georges Bank water. Analyses that use fixed isobath strata for the calculation of egg and larval abundance indices of zooplankton and ichthyoplankton may have a significant temporal/spatial bias.

Cod otoliths apparently incorporate isotopic forms of oxygen in equilibrium with their environment, thus suggesting that isotopic ratios can be an effective tool to trace the temperature history of individual fish. This tool has potentially important uses in understanding the effects of long-term temperature anomalies and how fish are able to respond to such variation.

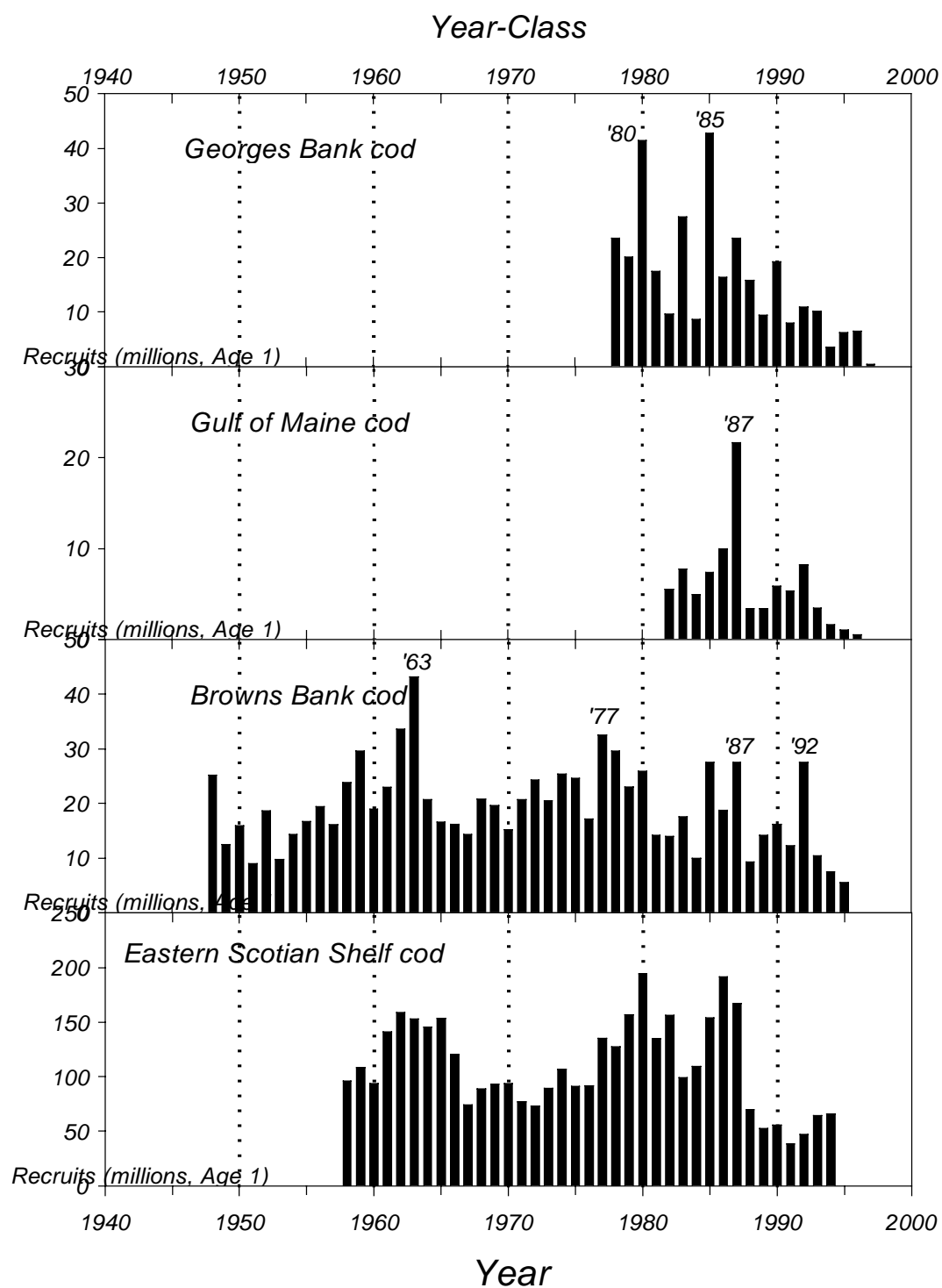


Figure 3.1.1. Recruitment (age 1, millions) of four Atlantic cod stocks in the Georges Bank, Gulf of Maine and Scotian Shelf regions. Data are given by year class, and are derived from VPA.

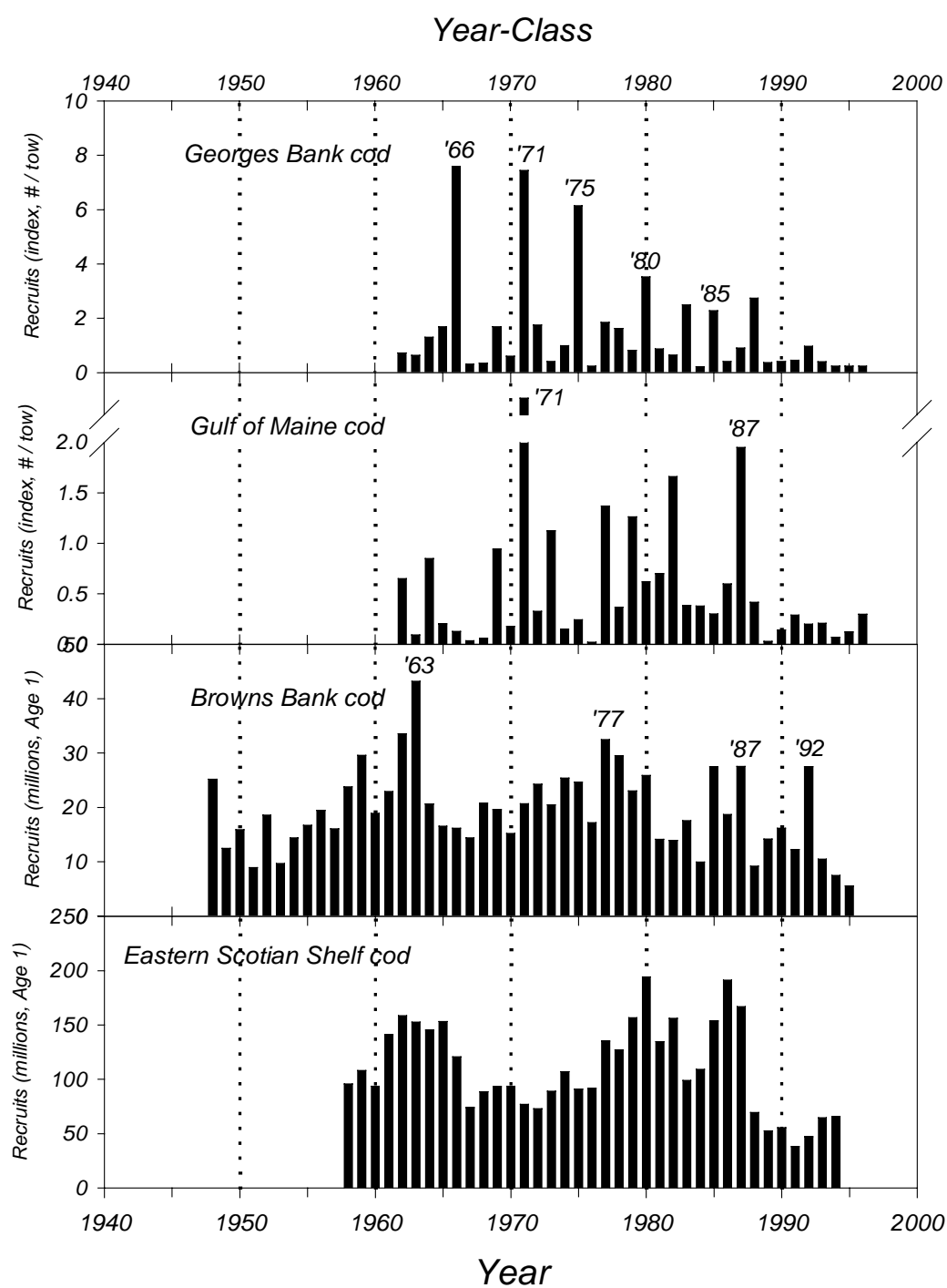


Figure 3.1.2. Recruitment indices(age 1) of four Atlantic cod stocks in the Georges Bank, Gulf of Maine and Scotian Shelf regions. Data are given by year class. For Georges Bank and the Gulf of Maine, data are relative indices of recruitment abundance (numbers of age 1 cod per standardized survey tow in autumn bottom trawl surveys). For Browns Bank and the E. Scotian Shelf, data are VPA, age 1 estimates.

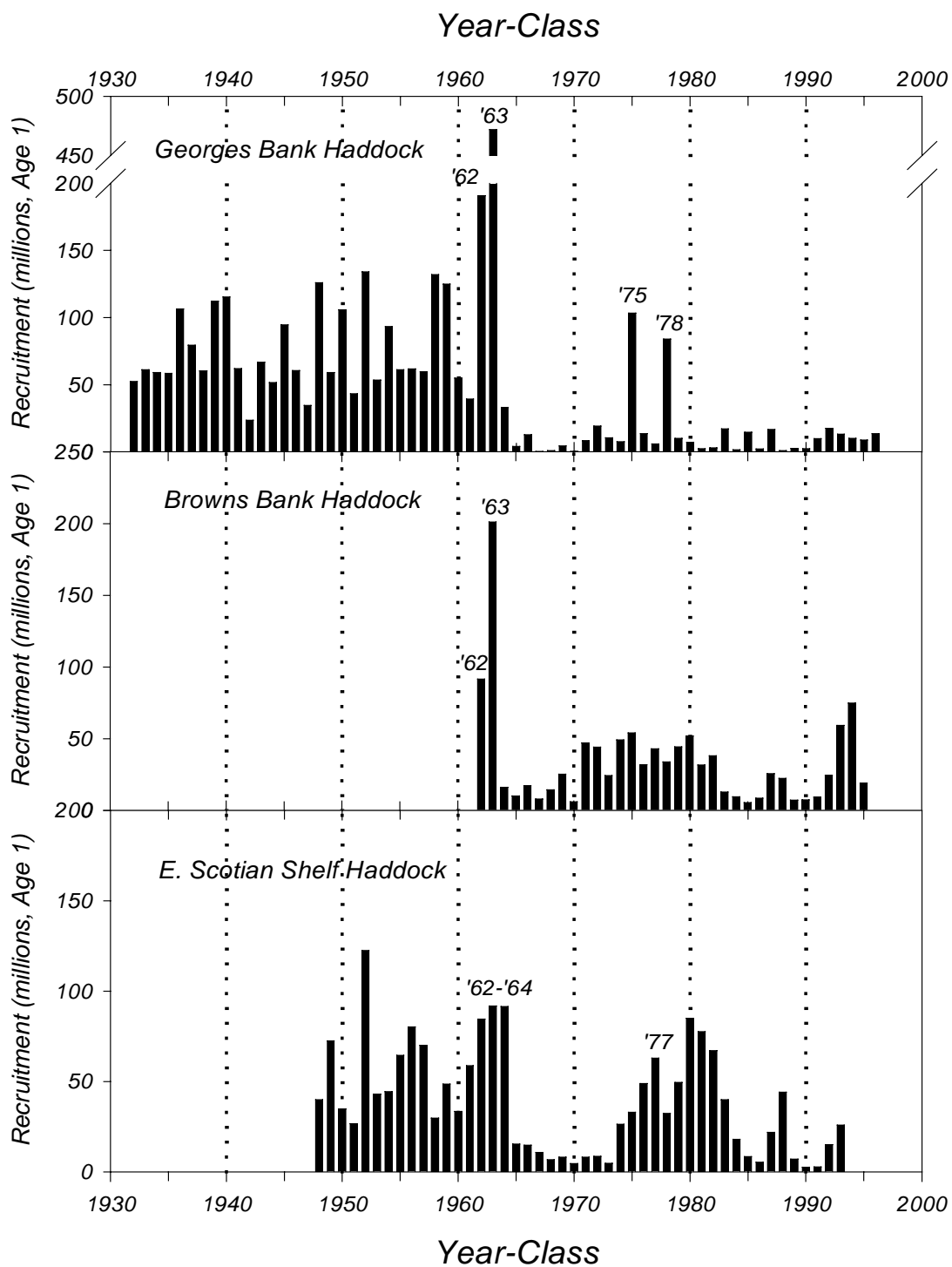


Figure 3.1.3. Recruitment (age 1, millions) of three haddock stocks in the Georges Bank, and Scotian Shelf regions. Data are given by year class, and are derived from VPA.

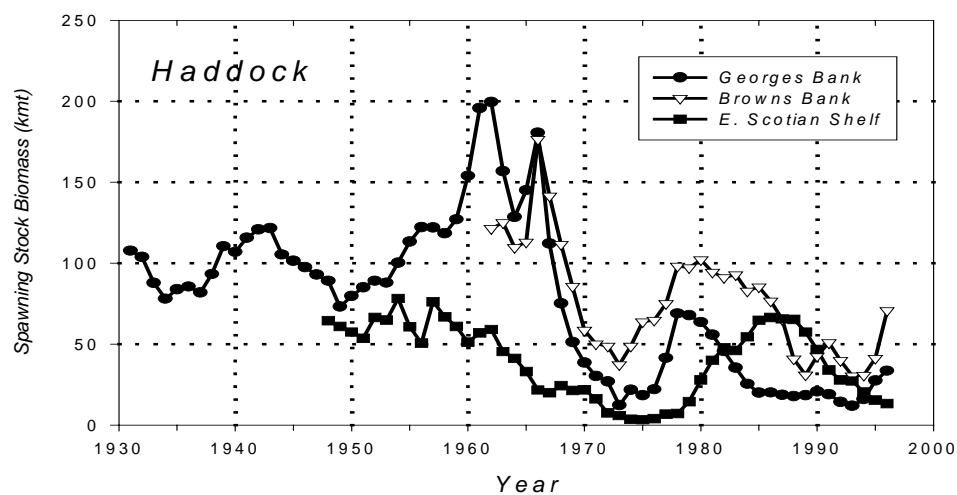
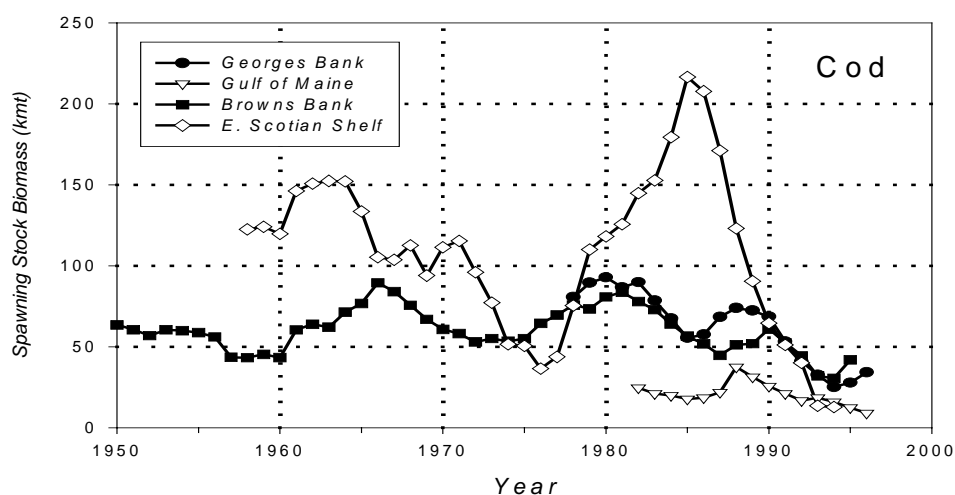


Figure 3.1.4. Trends in spawning stock biomass (SSB, thousands of mt) for Atlantic cod (upper) and haddock (lower) stocks in the Georges Bank, Gulf of Maine and Scotian Shelf areas. Data are from VPA.

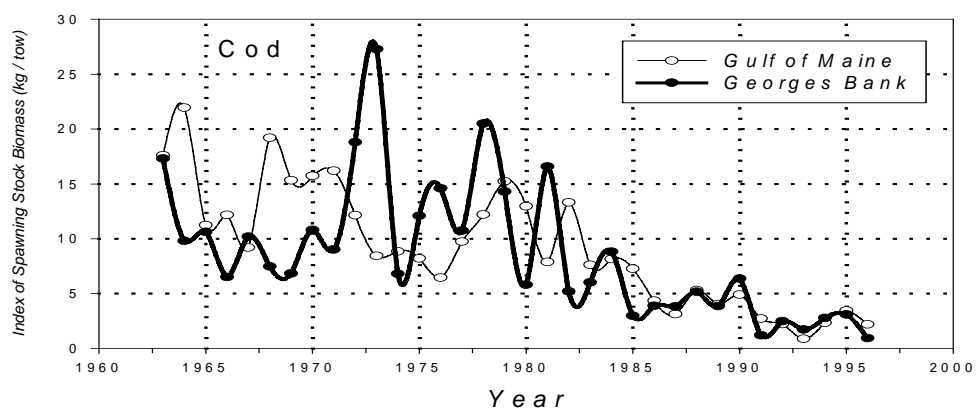


Figure 3.1.5. Smoothed trends in indices of spawning stock biomass (weight per tow of spawning fish) from autumn bottom trawl surveys, 1963-1996. Data are for Georges Bank and Gulf of Maine cod stocks.

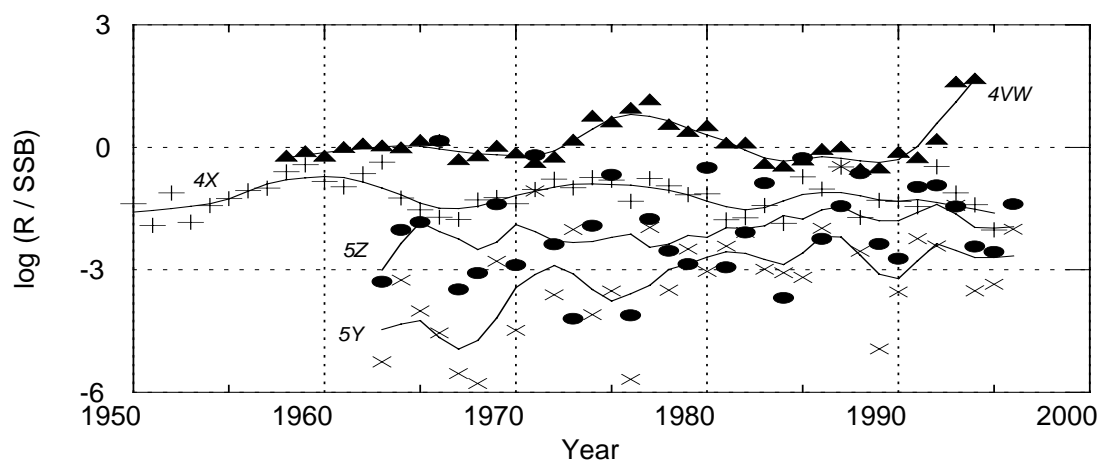


Figure 3.1.6. Trends in recruitment survival ($\log[R/SSB]$) of four cod stocks in the Georges Bank, Gulf of Maine and Scotian Shelf areas. A LOWESS smoother (tension=0.2) is fitted to each time-series. Series are: X=5Y, Gulf of Maine, ●=5Z, Georges Bank, +=4X, Browns Bank, ▲=4VW, E. Scotian Shelf. Data for Georges Bank and Gulf of Maine stocks are based on relative survey indices; Browns Bank and E. Scotian Shelf are from VPA.

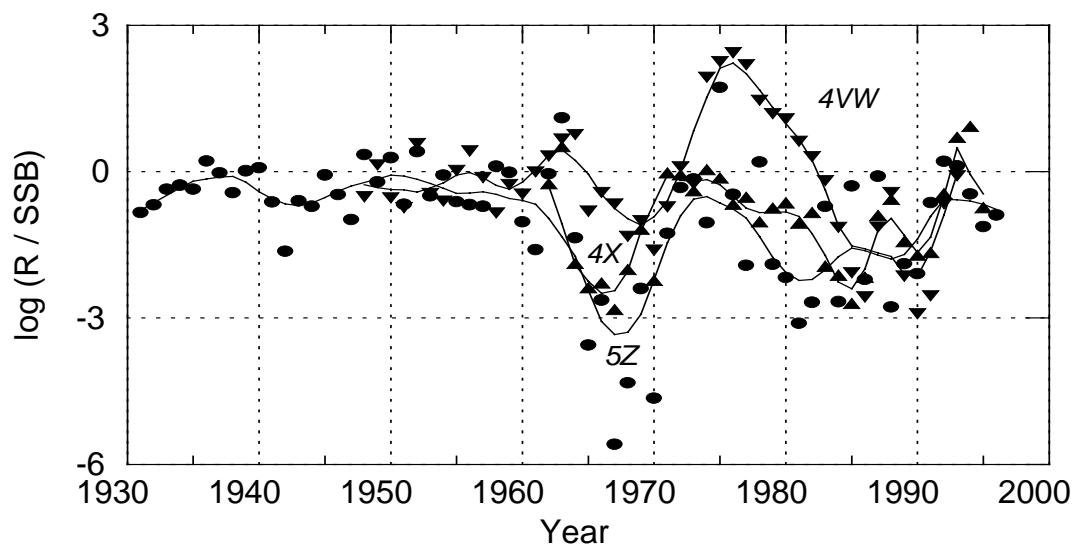


Figure 3.1.7. Trends in recruitment survival ($\log[R/SSB]$) of three haddock stocks in the Georges Bank, and Scotian Shelf areas. A LOWESS smoother (tension=0.15) is fitted to each time-series. Series are: ●=5Z, Georges Bank, ▲=4X, Browns Bank, ▼=4VW, E. Scotian Shelf. Data are based on VPA.

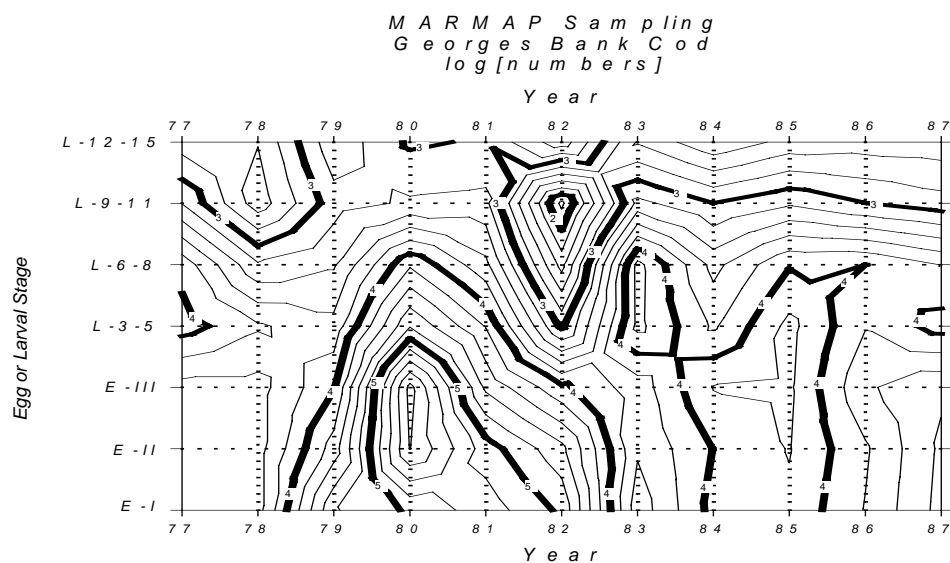


Figure 3.2.1. Contours of relative abundance (log(numbers)) of various early life stages of cod taken in MARMAP samples on Georges Bank and the Middle Atlantic Bight, 1977-1987. Stages are: Egg I (E-I), Egg II (E-II), Egg-III (E-III), larvae 3-5 mm (L-3-5), larvae 6-8 mm (L-6-8), larvae 9-11 mm (L-9-11), and larvae 12-15 mm (L-12-15). Indices are based on sampling from March-June.

[Note Figure 3.2.2 is on the next page]

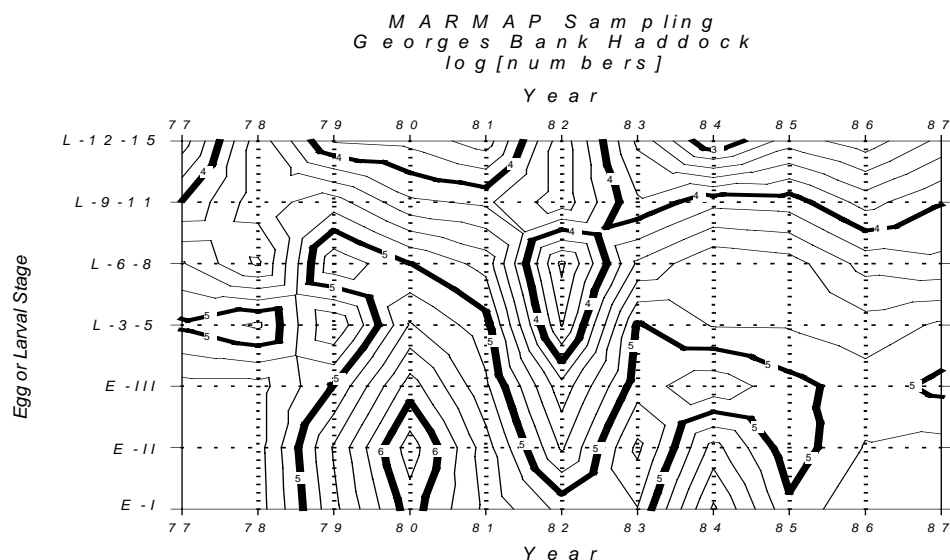


Figure 3.2.3. Contours of relative abundance (log(numbers)) of various early life stages of haddock taken in MARMAP samples on Georges Bank and the Middle Atlantic Bight, 1977-1987. Stages are: Egg I (E-I), Egg II (E-II), Egg-III (E-III), larvae 3-5 mm (L-3-5), larvae 6-8 mm (L-6-8), larvae 9-11 mm (L-9-11), and larvae 12-15 mm (L-12-15). Indices are based on sampling from March-June.

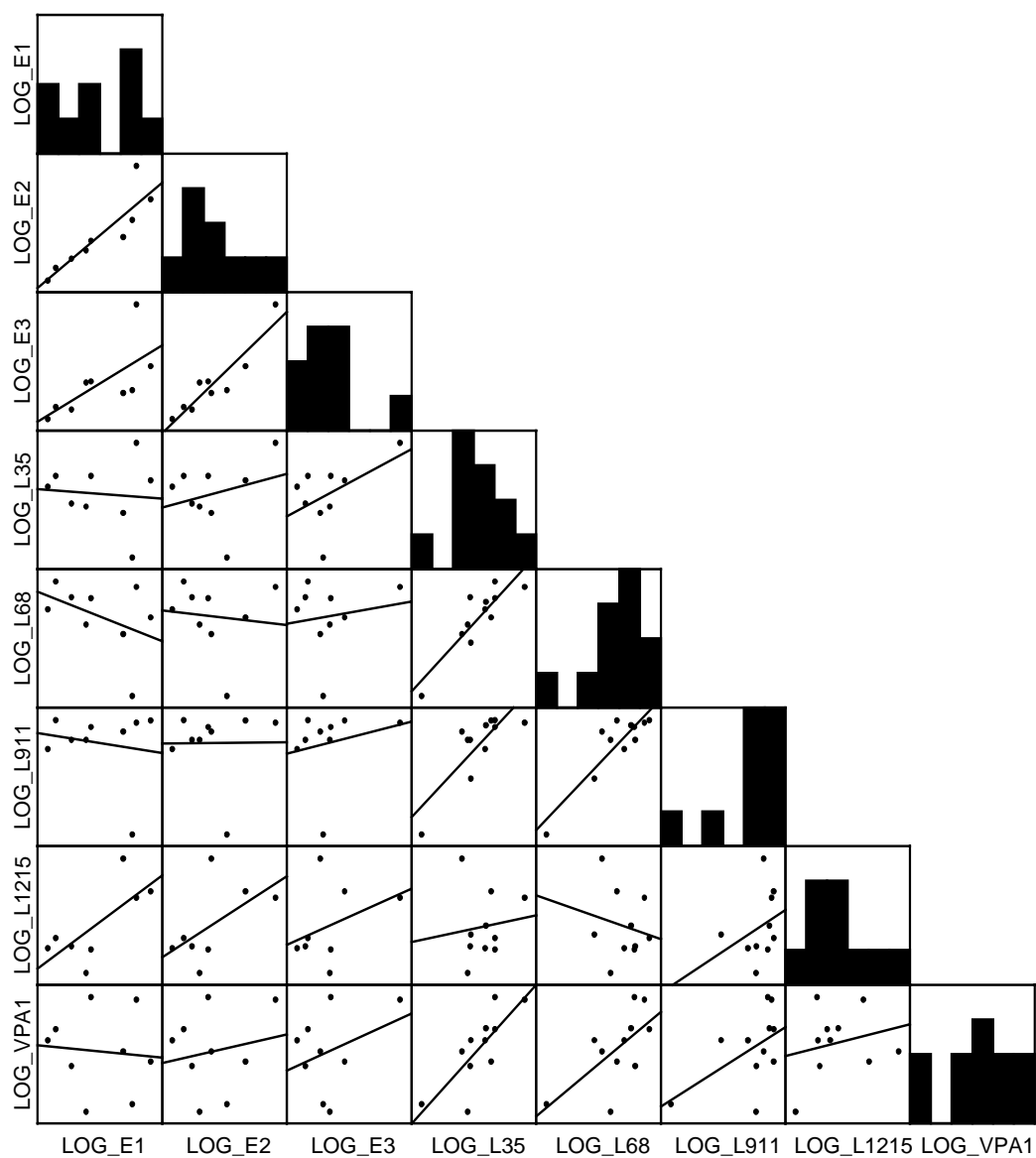


Figure 3.2.2. Correlations among abundance indices for various life history stages of the Georges Bank cod stock, 1977-1987. Data are abundance measures from MARMAP surveys of egg (E) and larvae (L), in various size/age categories (see key in Figure 3.1.1). Age 1 abundance based on VPA for 1977-1987 year classes is included.

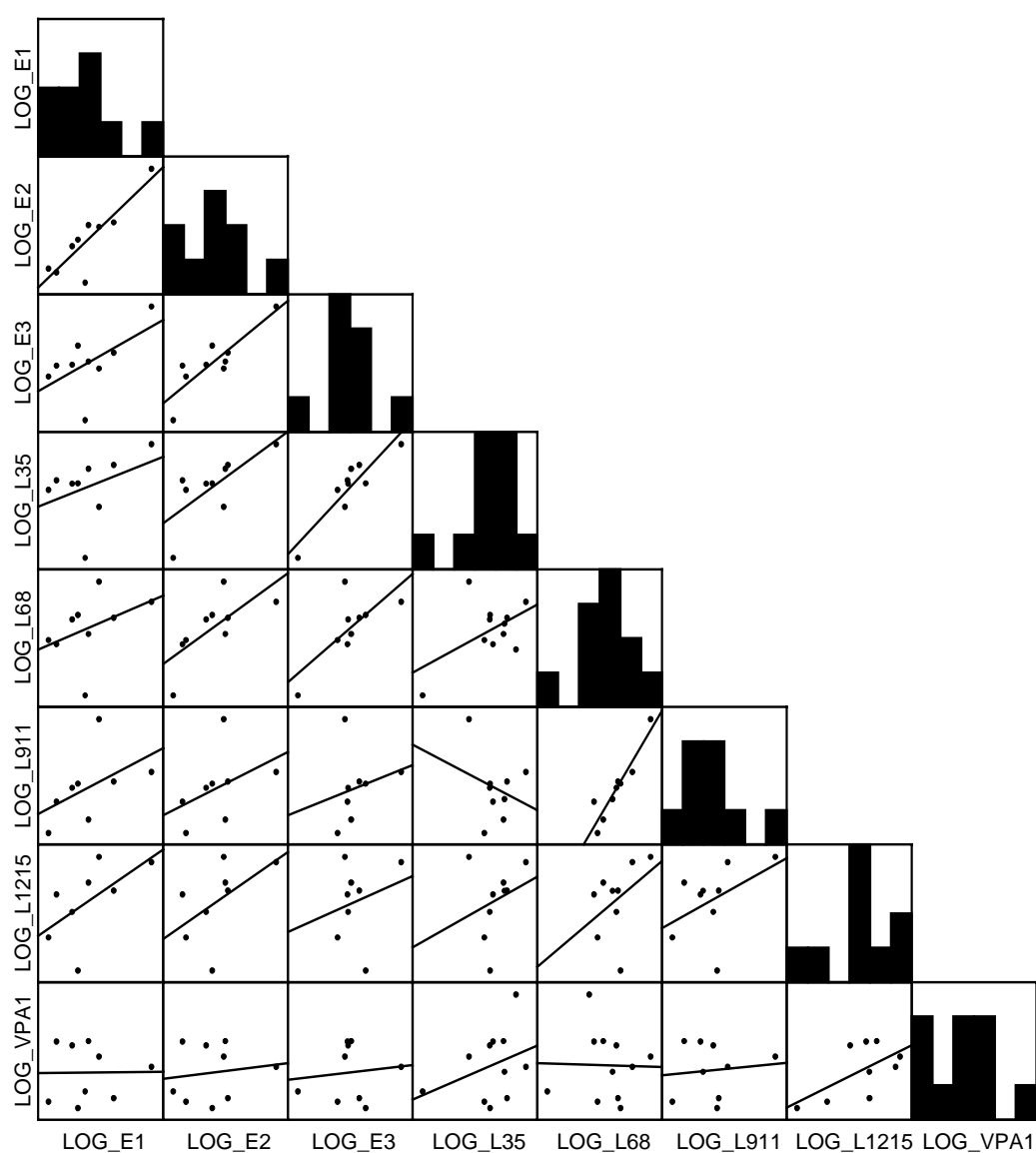


Figure 3.2.4. Correlations among abundance indices for various life history stages of the Georges Bank haddock stock, 1977-1987. Data are abundance measures from MARMAP surveys of egg (E) and larvae (L), in various size/age categories (see key in Figure 3.1.3). Age 1 abundance based on VPA for 1977-1987 year classes is included.

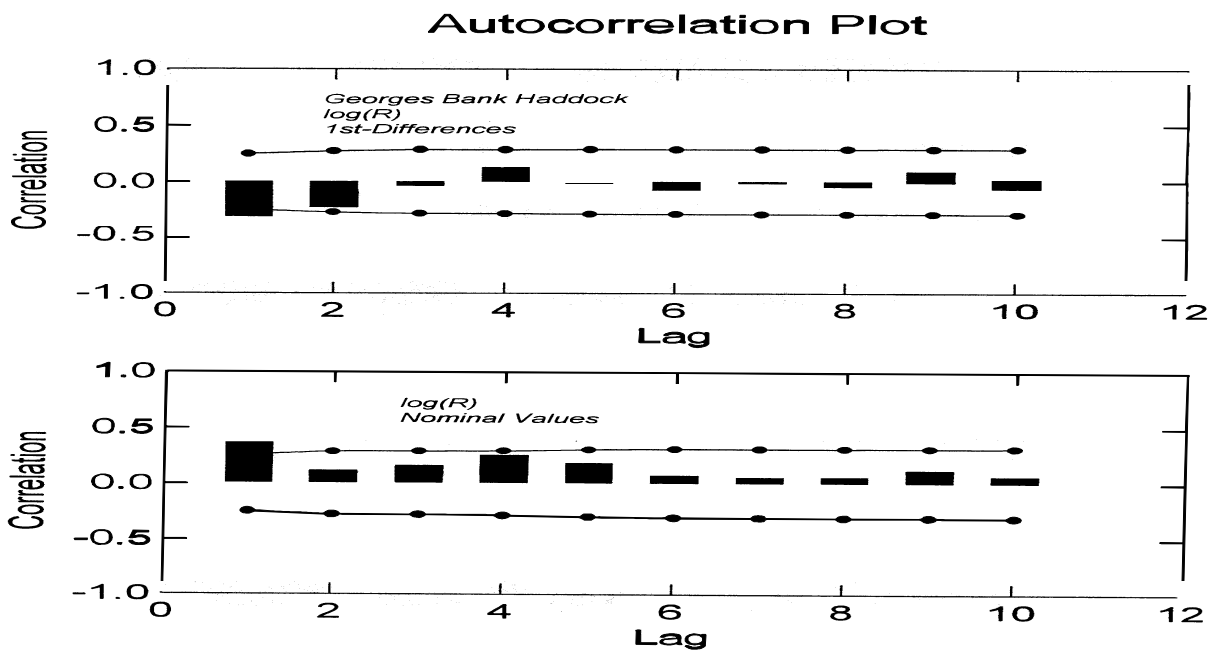


Figure 3.2.5. Tests of autocorrelation of log(recruitment) for the Georges Bank haddock stock, 1931-1996. Data are 1st-differenced (upper) and nominal (lower). When bars extend beyond the lines they are statistically significant.

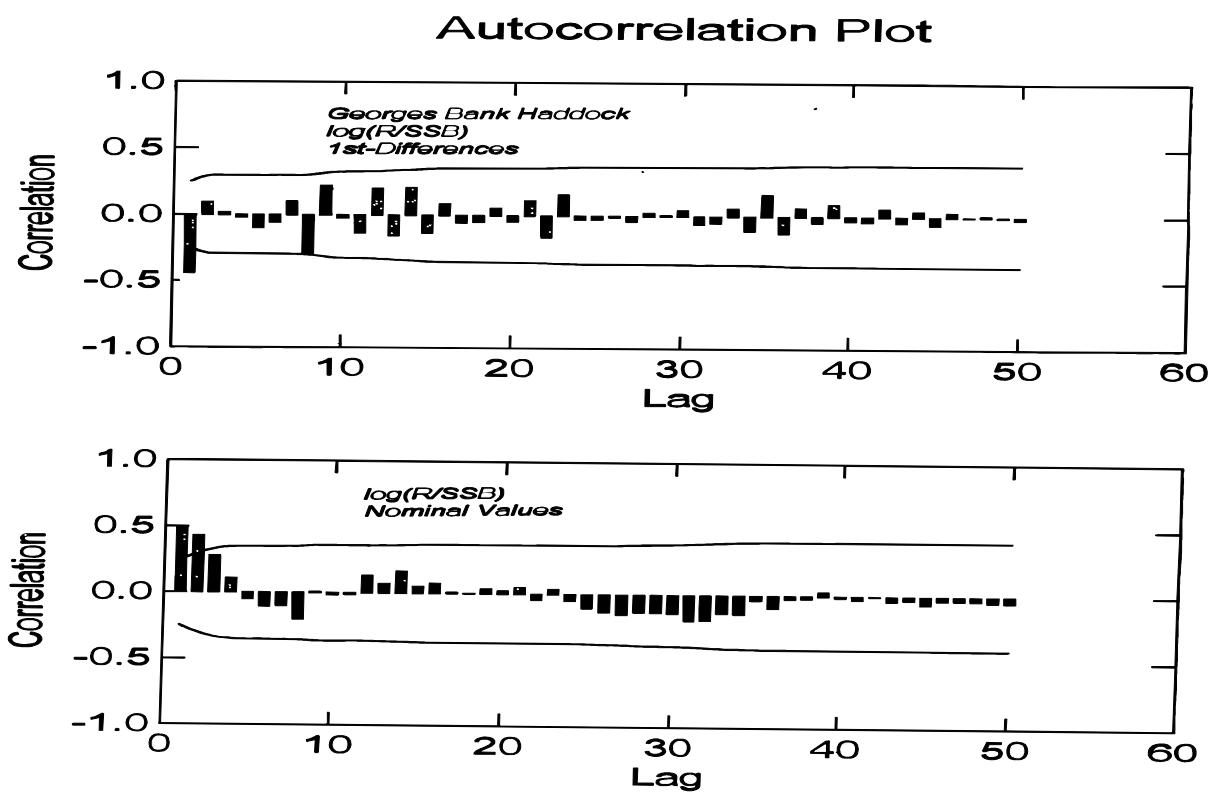


Figure 3.2.6. Tests of autocorrelation of $\log(R/SSB)$ for the Georges Bank haddock stock, 1931-1996. Data are 1st-differenced (upper) and nominal (lower). When bars extend beyond the lines they are statistically significant

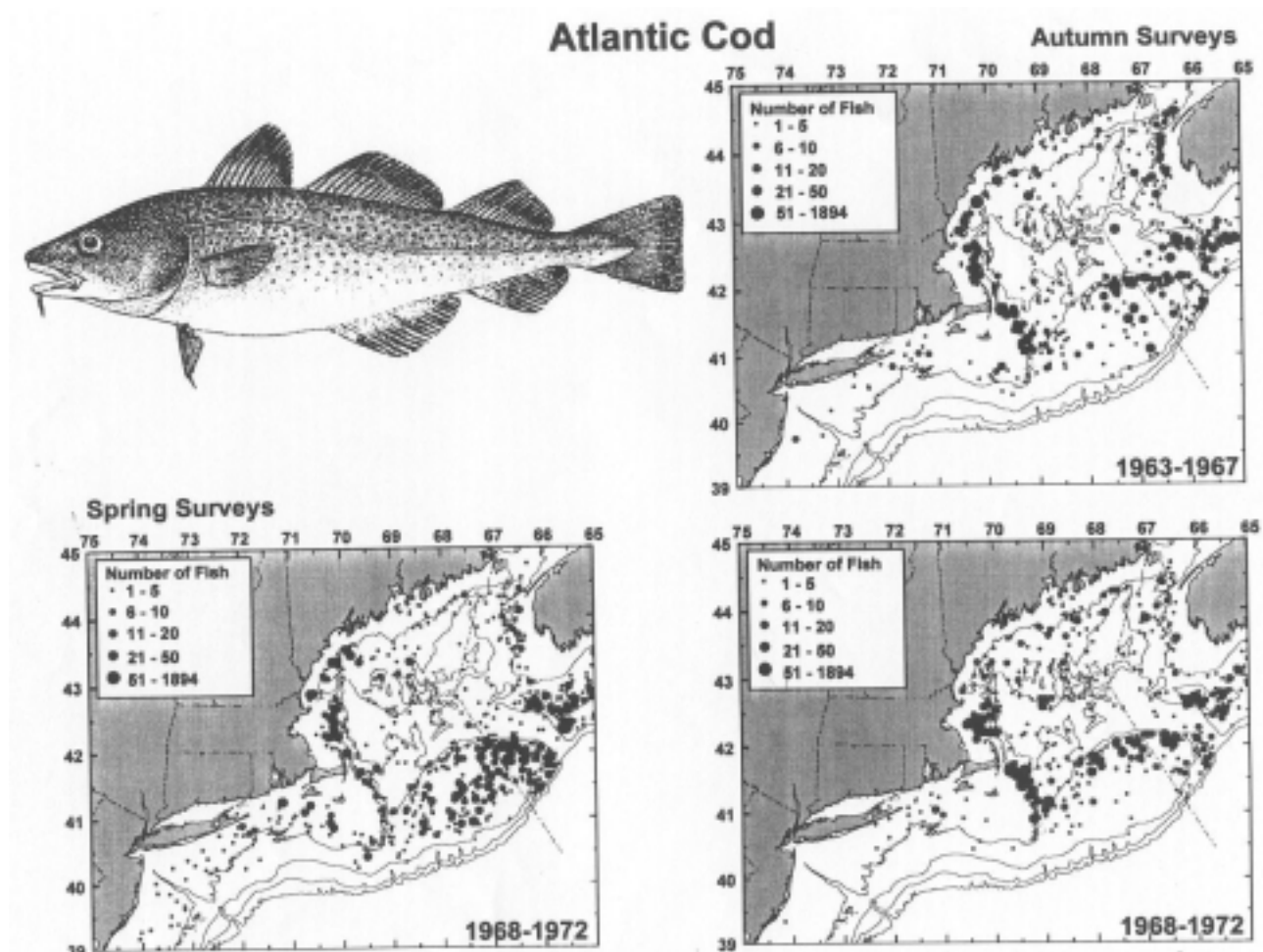


Figure 3.2.7a. Distribution of Atlantic cod in spring and autumn bottom trawl surveys, 1963–1972.

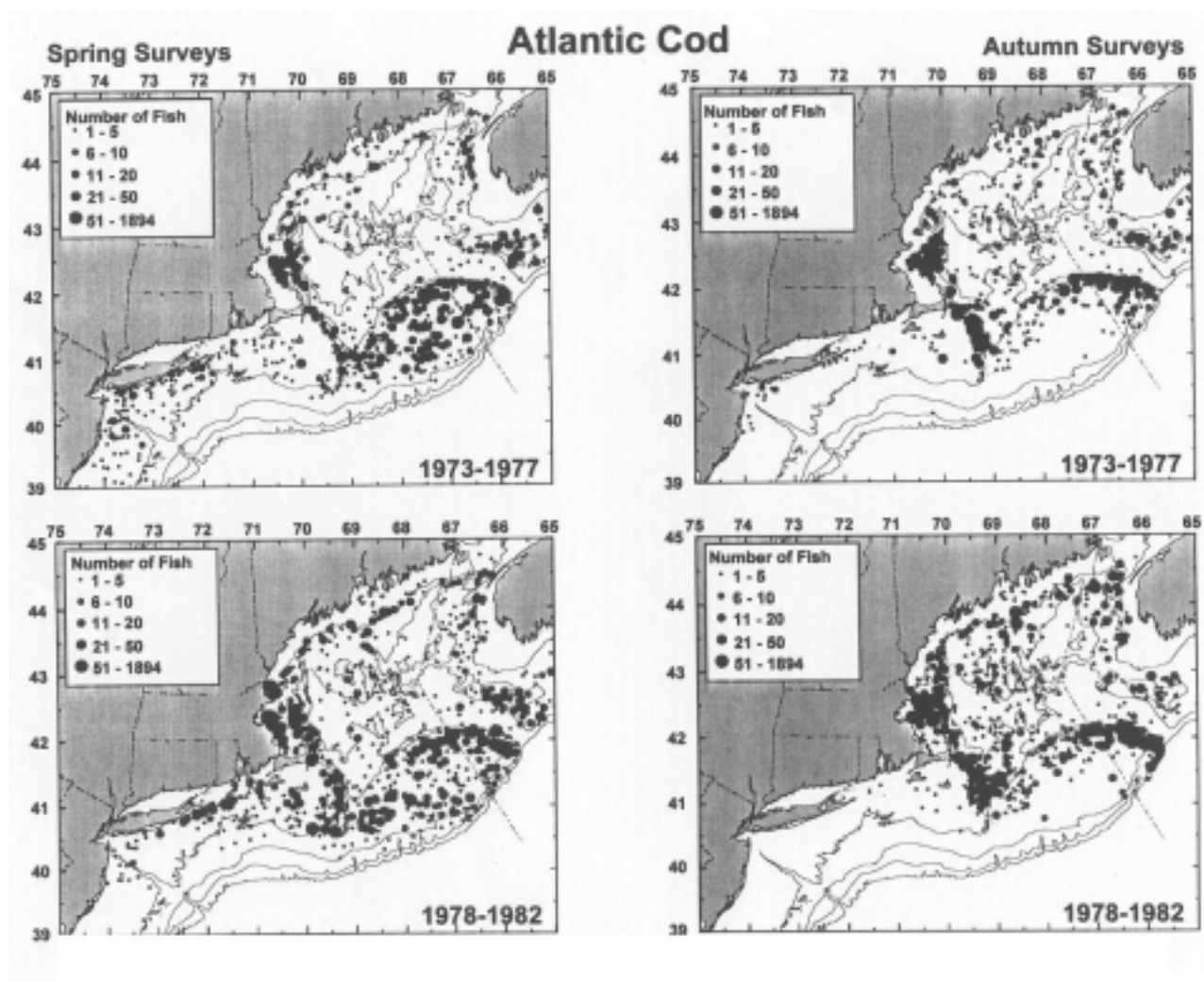


Figure 3.2.7b. Distribution of Atlantic cod in spring and autumn bottom trawl surveys, 1973–1982.

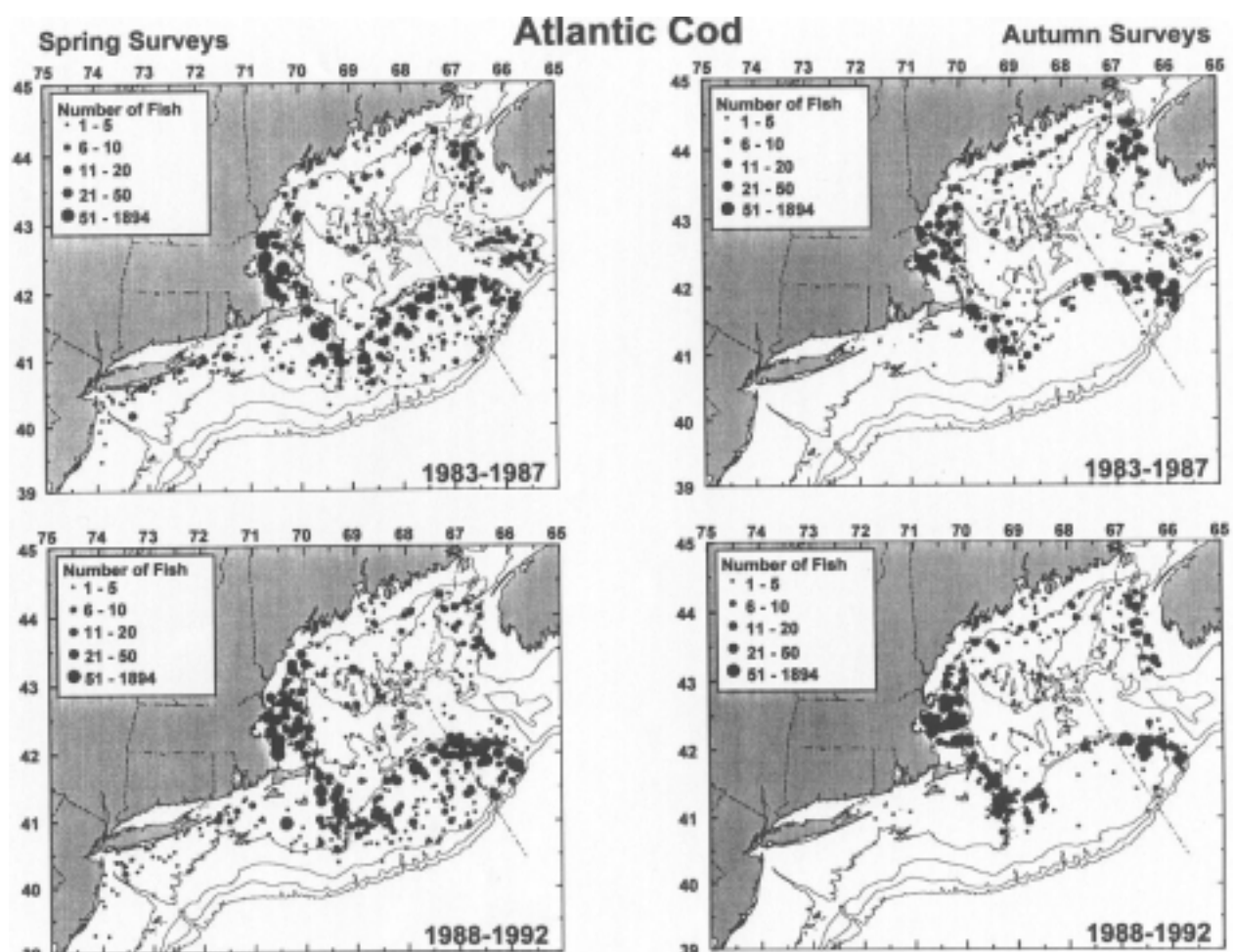


Figure 3.2.7c. Distribution of Atlantic cod in spring and autumn bottom trawl surveys, 1983–1992.

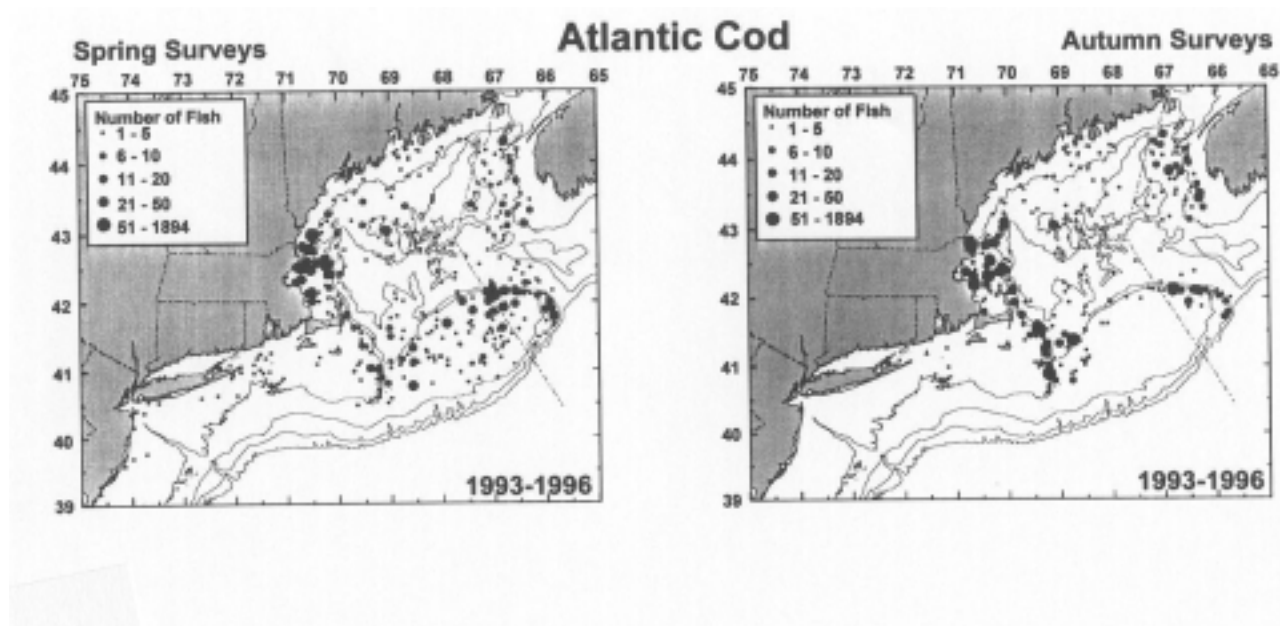


Figure 3.2.7d. Distribution of Atlantic cod in spring and autumn bottom trawl surveys, 1993–1996.

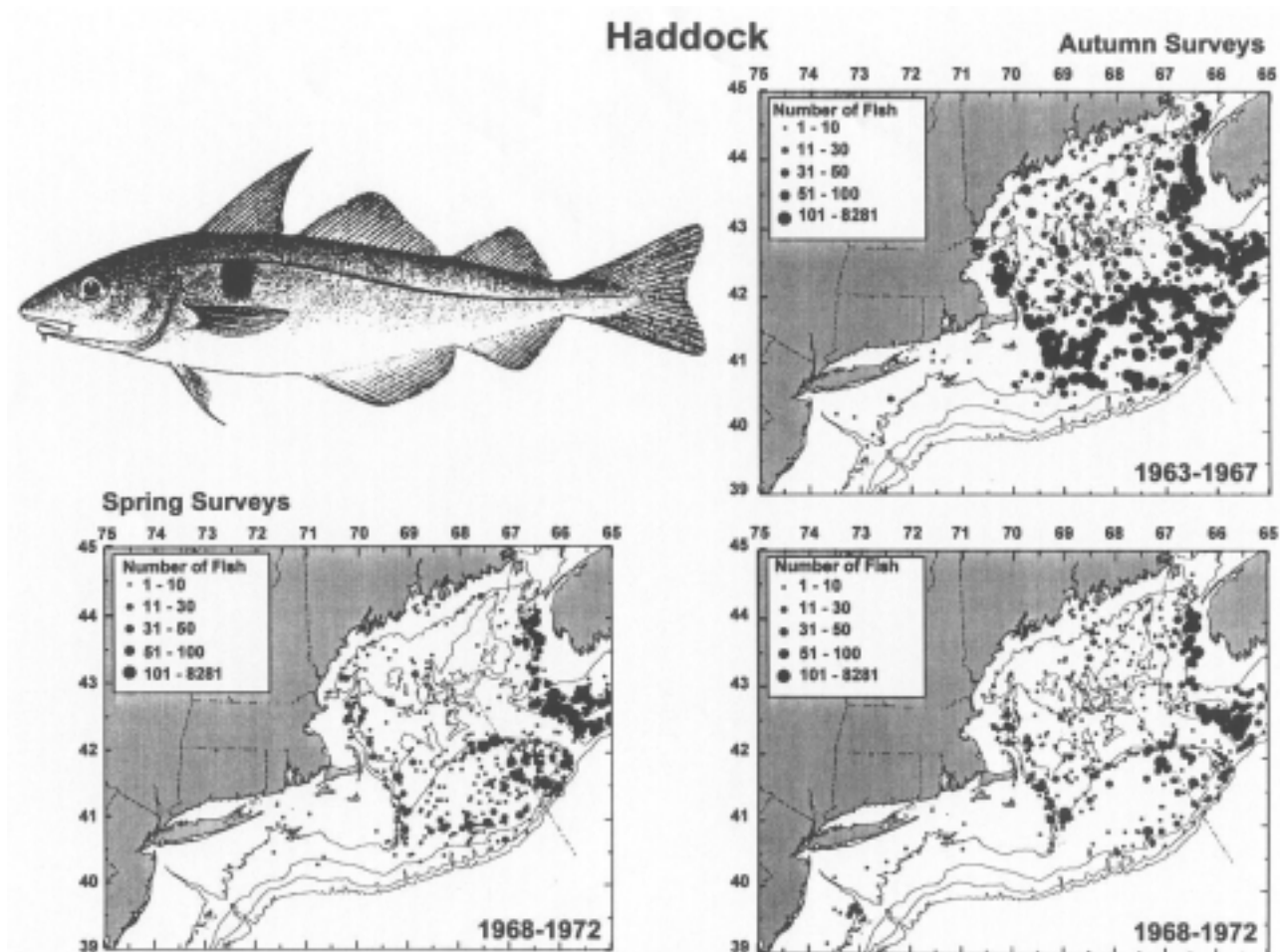


Figure 3.2.8a. Distribution of haddock in spring and autumn bottom trawl surveys, 1963-1972.

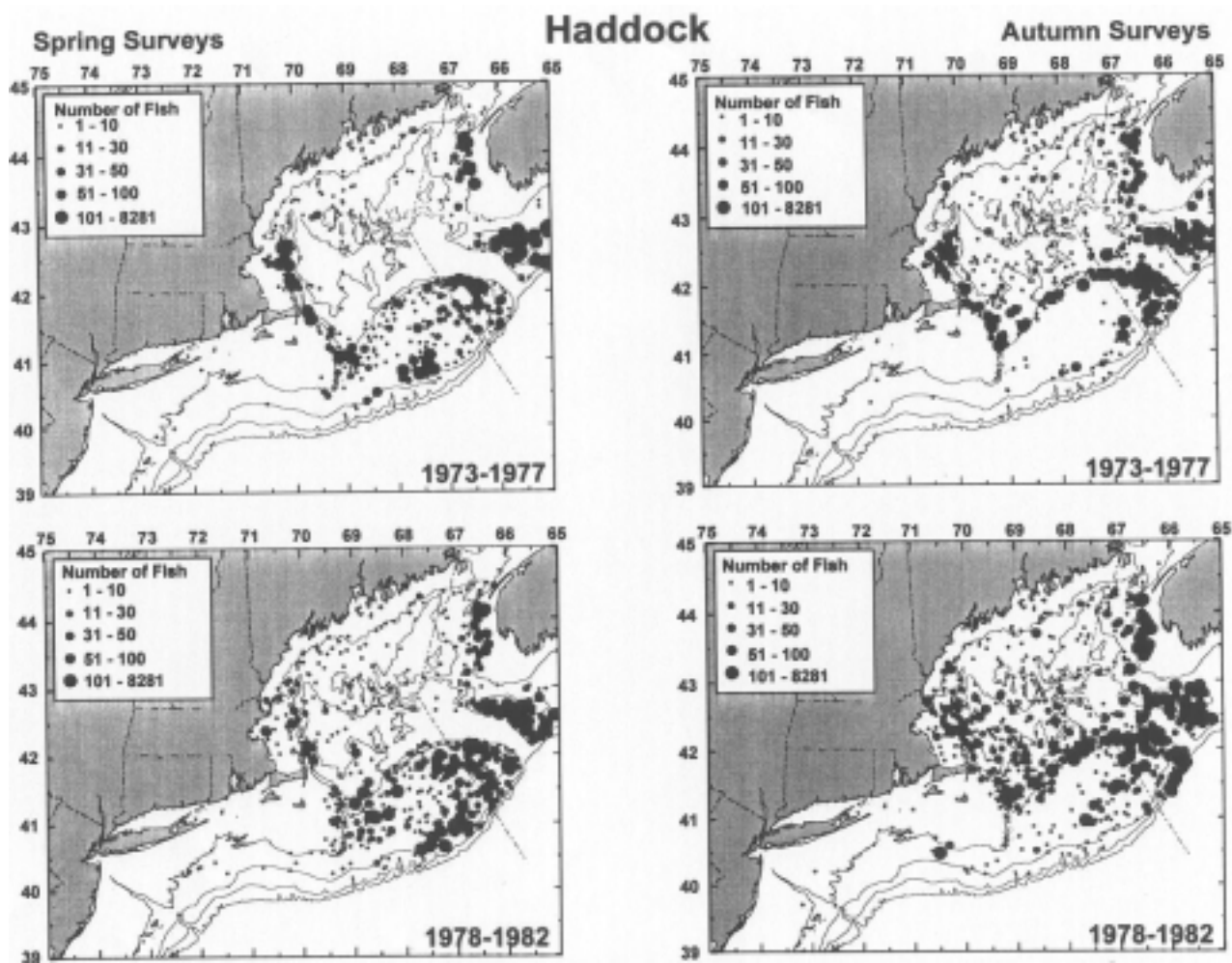


Figure 3.2.8b. Distribution of haddock in spring and autumn bottom trawl surveys, 1973–1982.

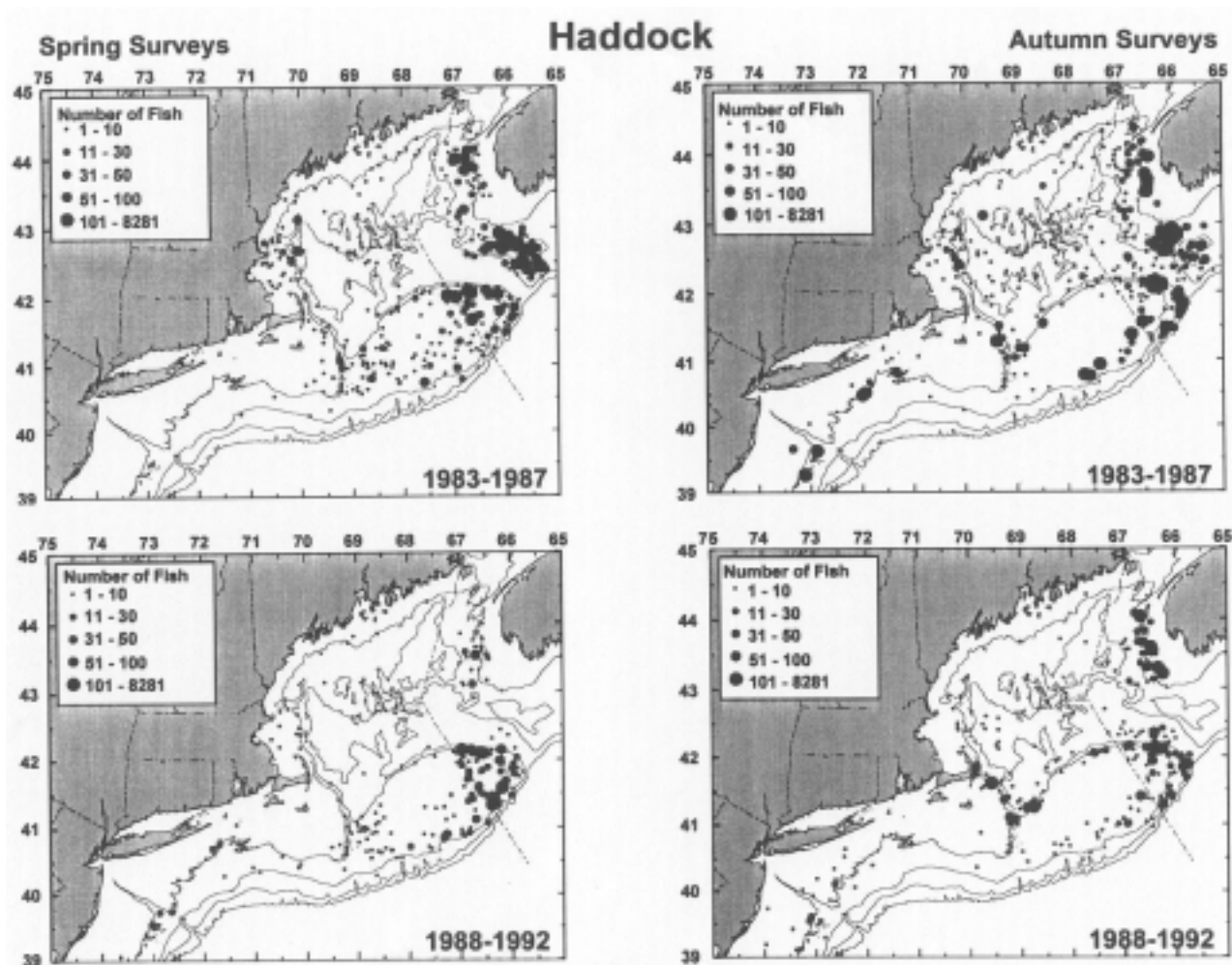


Figure 3.2.8c. Distribution of haddock in spring and autumn bottom trawl surveys, 1983–1992.

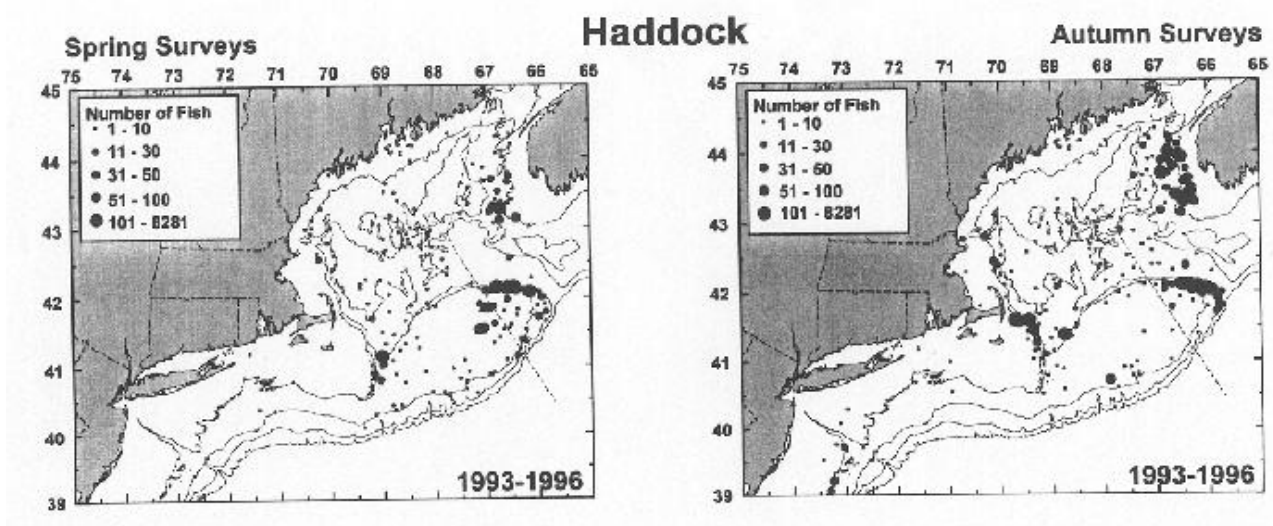


Figure 3.2.8d. Distribution of haddock in spring and autumn bottom trawl surveys, 1993–1996.

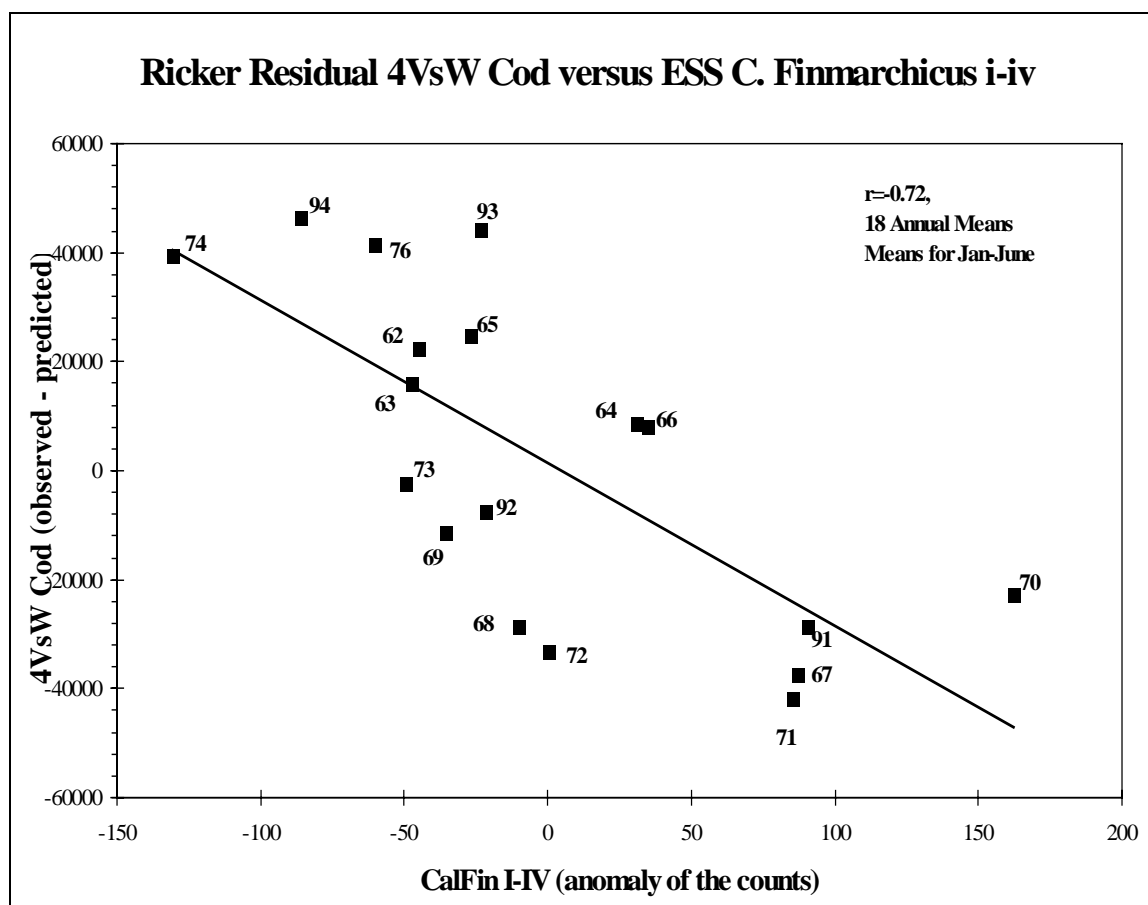


Figure 3.3. Ricker Residual 4VsW Cod versus ESS C. Finmarchicus i-iv.

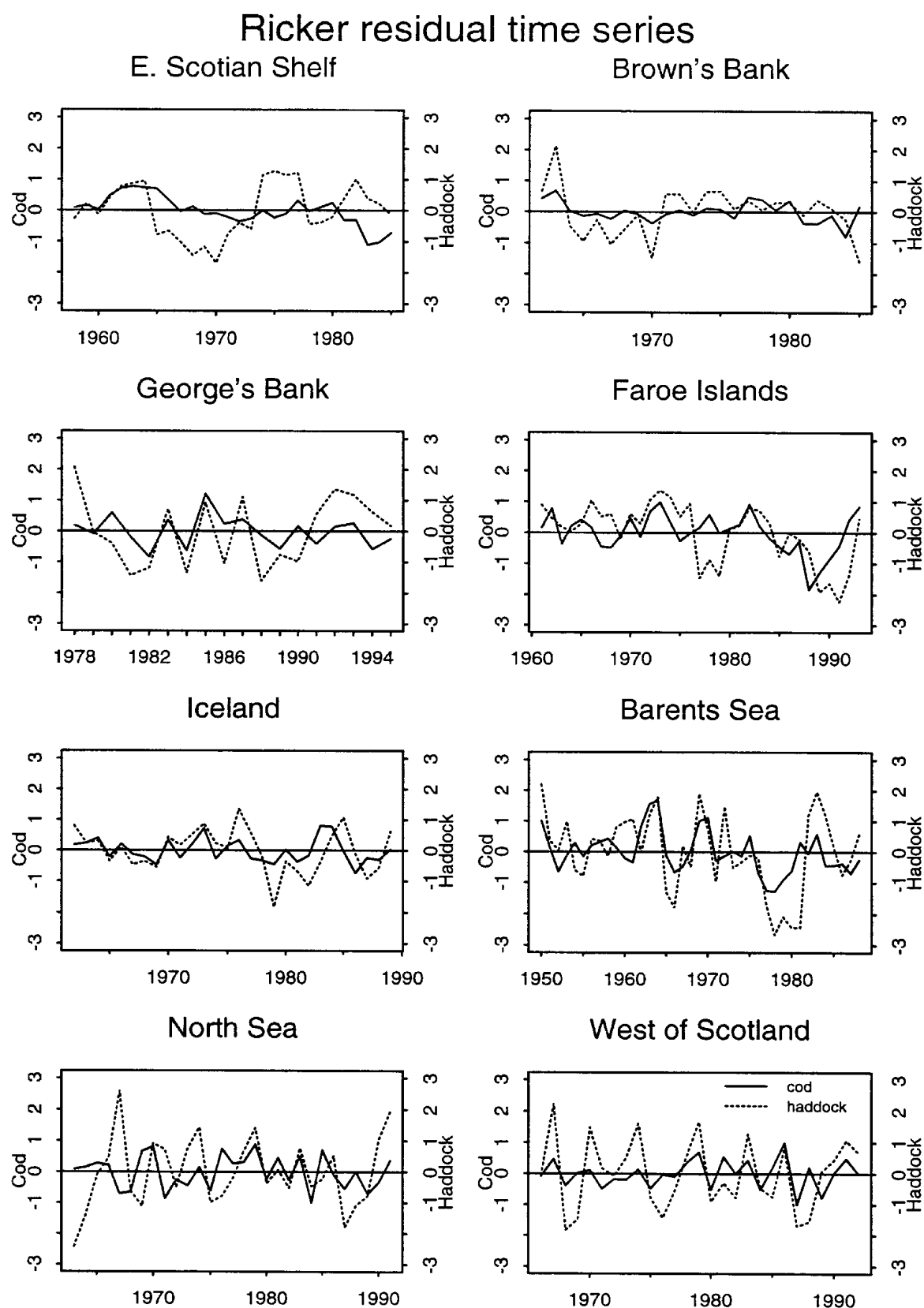


Figure 3.4.1. Time series of residuals from Ricker stock-recruitment relationships fitted to 8 pairs of regional cod and haddock stocks.

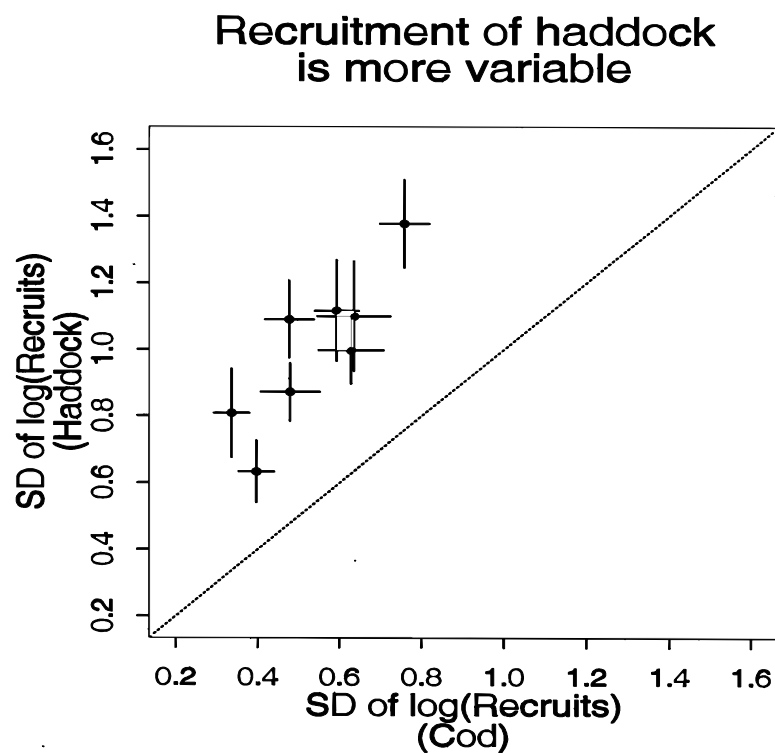


Figure 3.4.2. Standard deviation (SD) of log (recruitment) of cod vs. haddock in 8 stock areas in the North Atlantic.

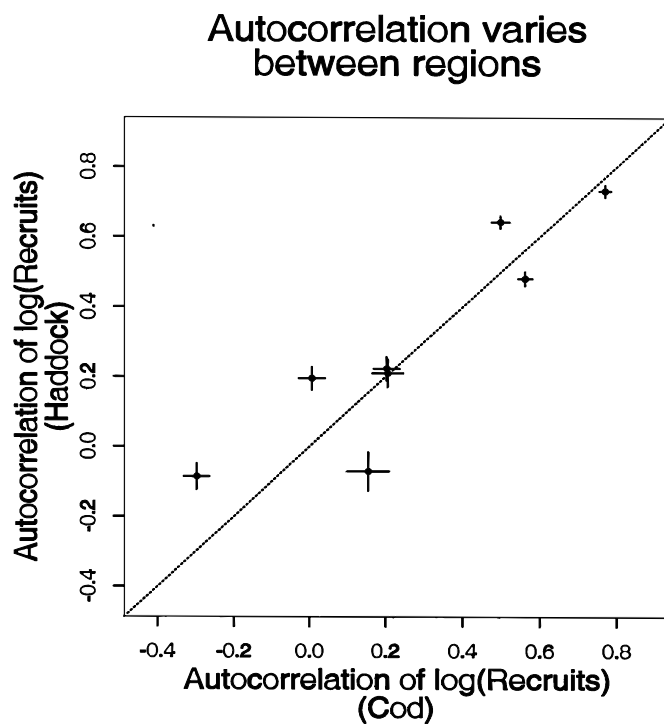


Figure 3.4.3. Autocorrelation of log(recruitment) of cod vs. haddock in 8 stock areas of the North Atlantic.

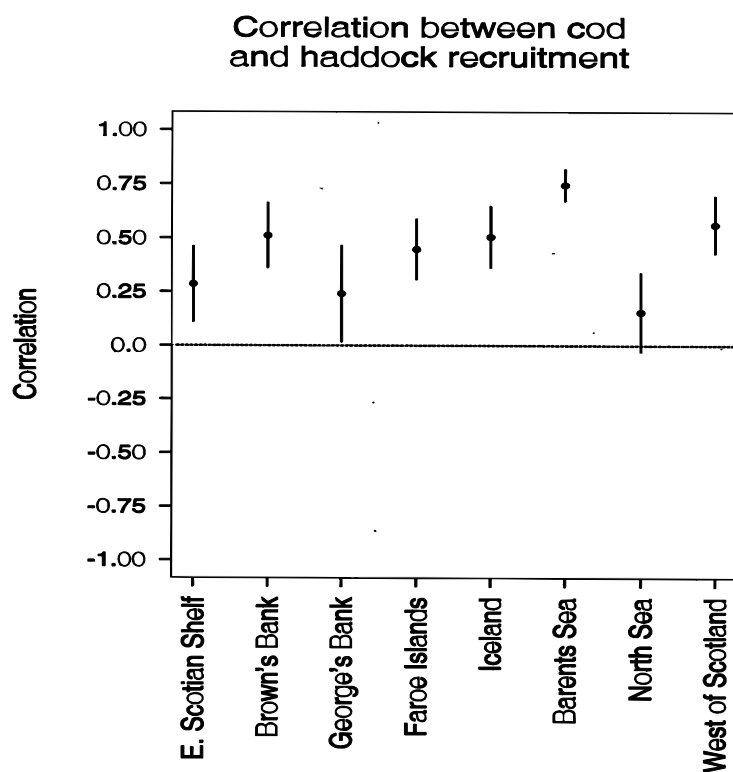


Figure 3.4.4. Correlation, r , between annual cod and haddock recruitment in 8 regions of the North Atlantic.

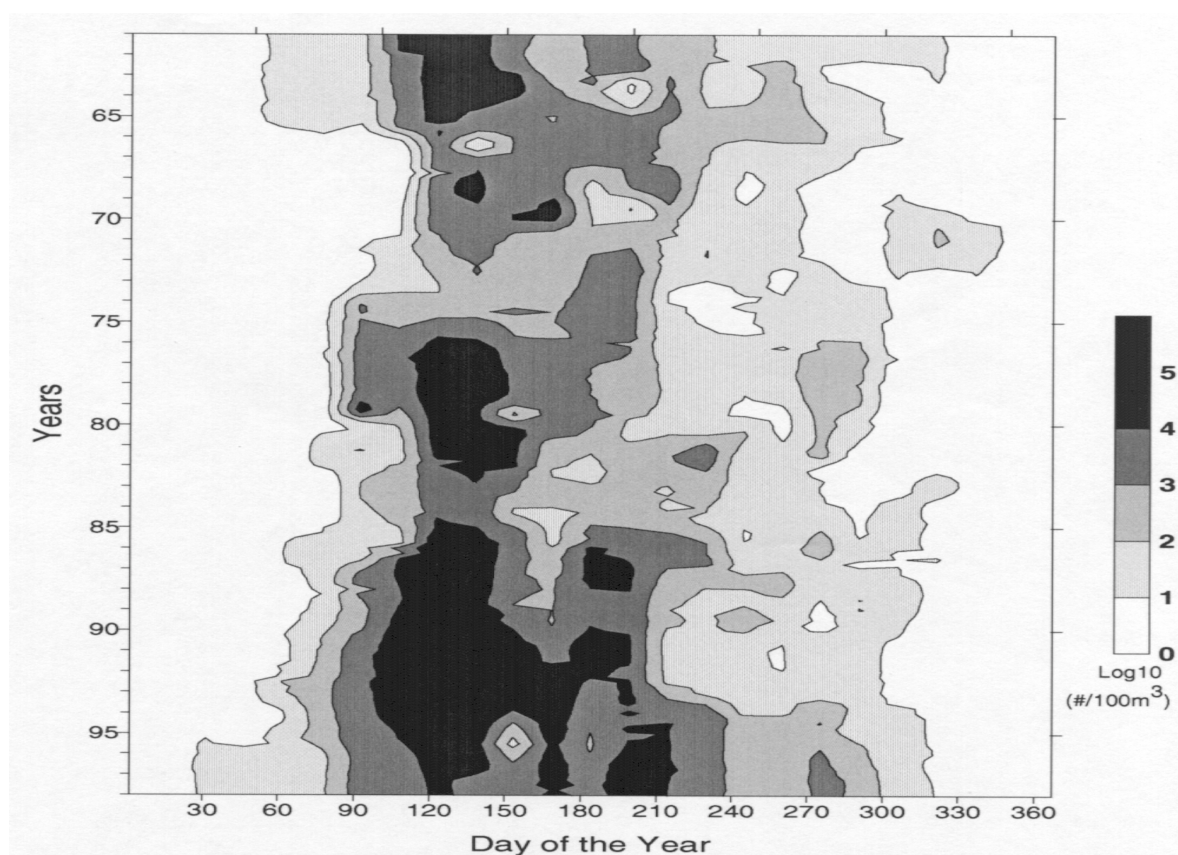


Figure 3.7.1. Abundance of *Calanus finmarchicus*, c1-4, between Massachusetts and Cape Sable (10 m), 1961–1997. Data are from NOAA/NEFSC CPR surveys.

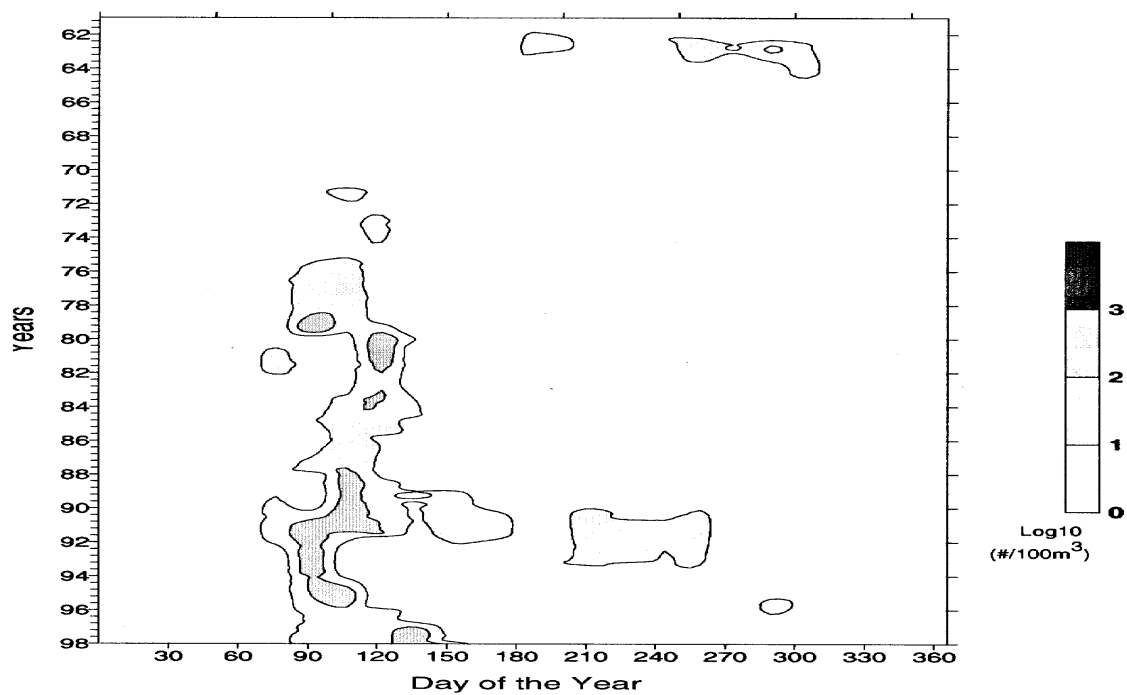


Figure 3.7.2. Abundance of copepod nauplii between Massachusetts and Cape Sable (10 m), 1961-1997. Data are from NOAA/NEFSC CPR surveys.

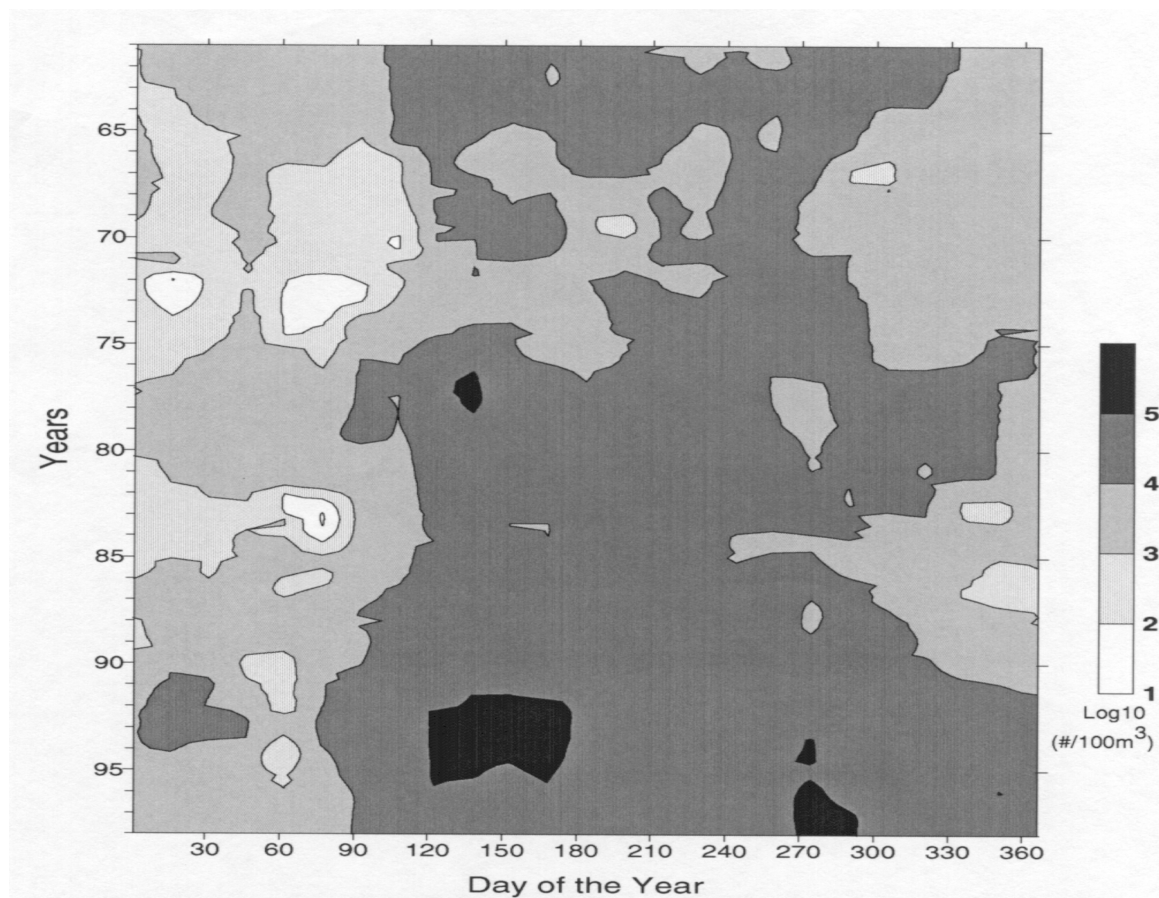


Figure 3.7.3. Abundance of total copepoda, all stages, between Massachusetts and Cape Sable (10 m), 1961-1997. Data are from NOAA/NEFSC CPR surveys.

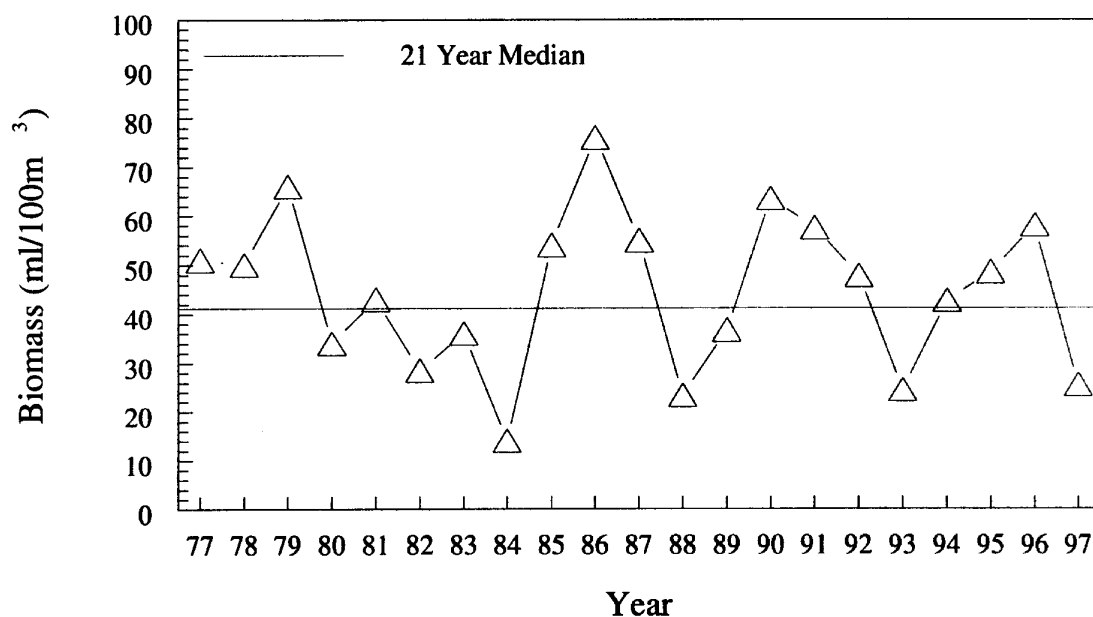


Figure 3.7.4. Annual median zooplankton biomass on Georges Bank during early spring. Data are from NOAA/NEFSC MARMAP surveys.

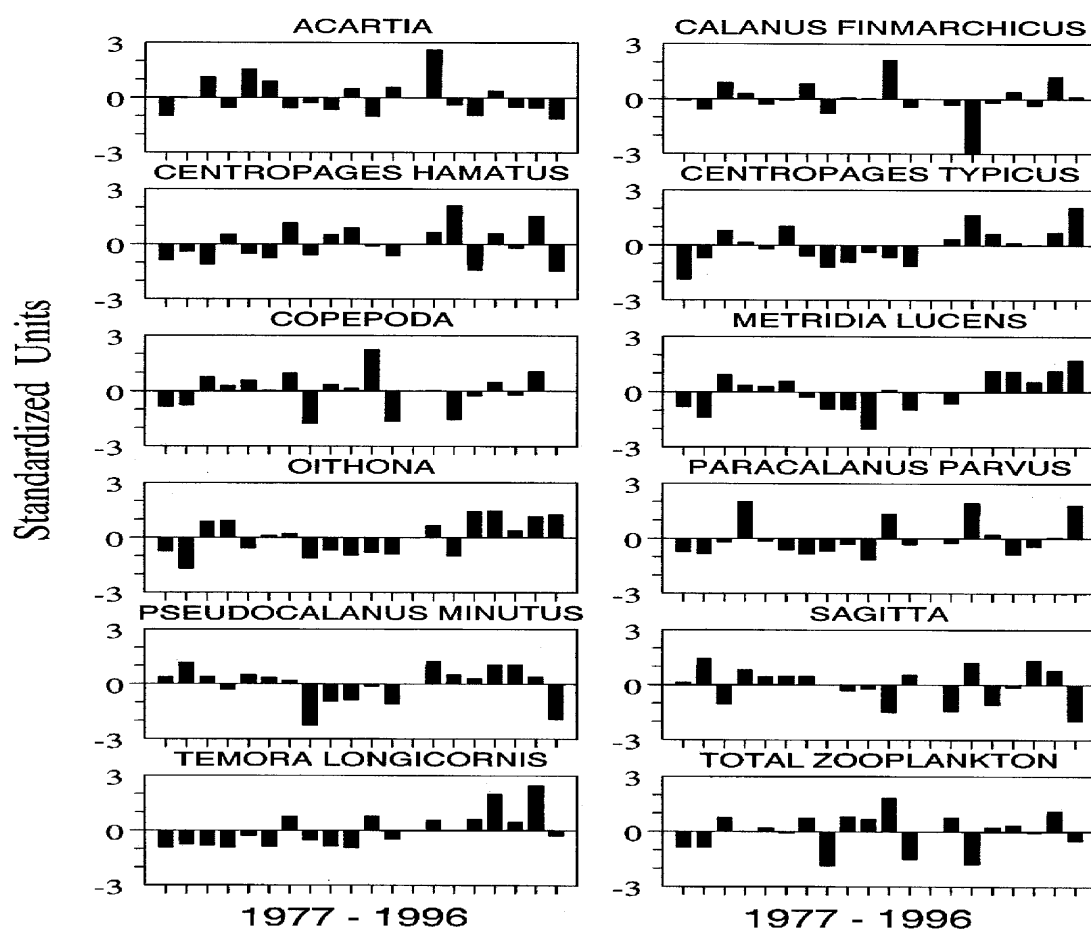


Figure 3.7.5. Standardized departures of mean annual plankton abundances for various species and groups during 'spring' (15 February-15 May) on Georges Bank, 1977-1996.

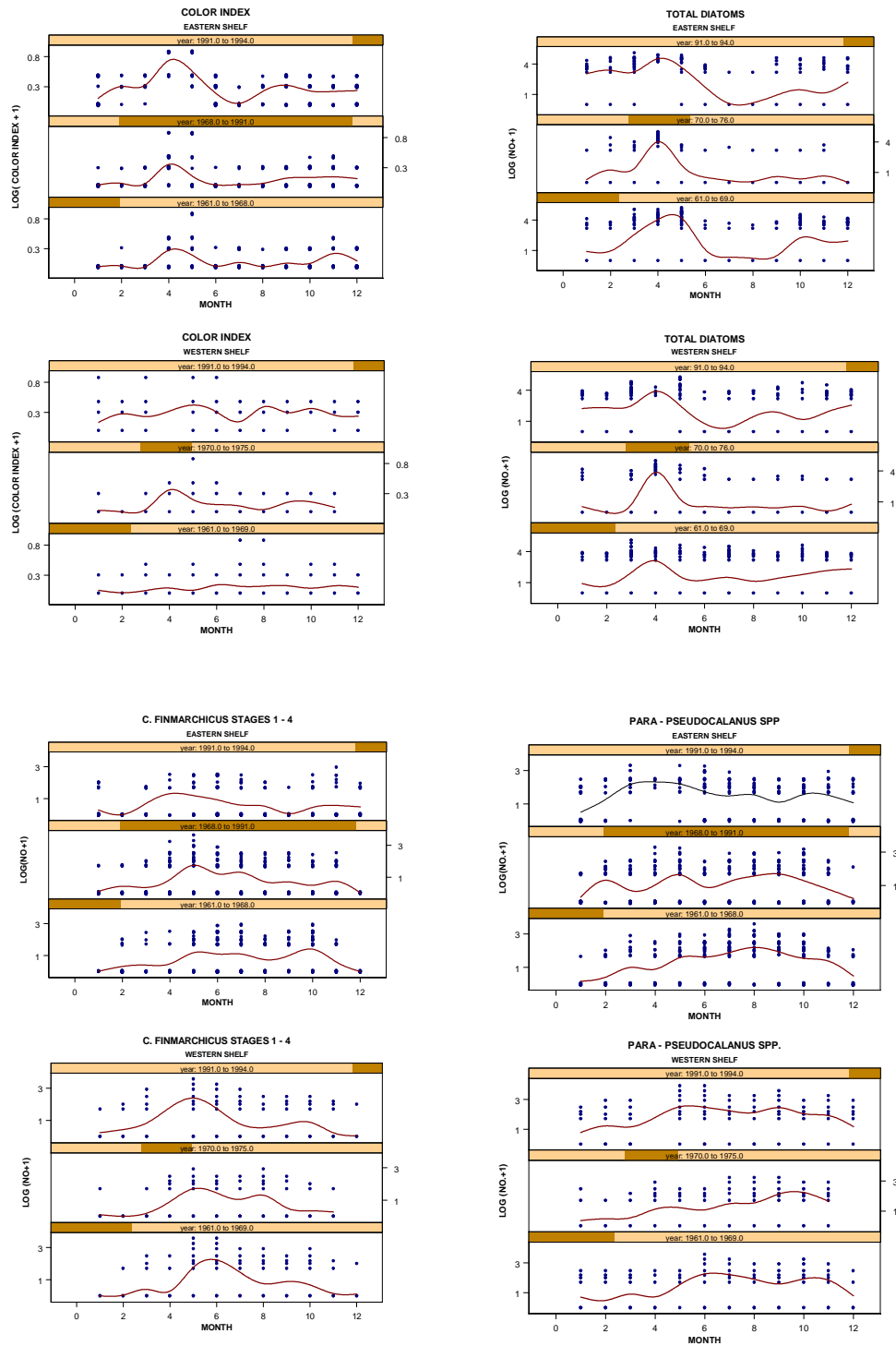


Figure 3.8.1. Seasonal cycles in abundance of various taxa on the eastern and western Scotian Shelf, for three different time periods. Dots represent data points and the lines are least squares cubic spline smoother fits.

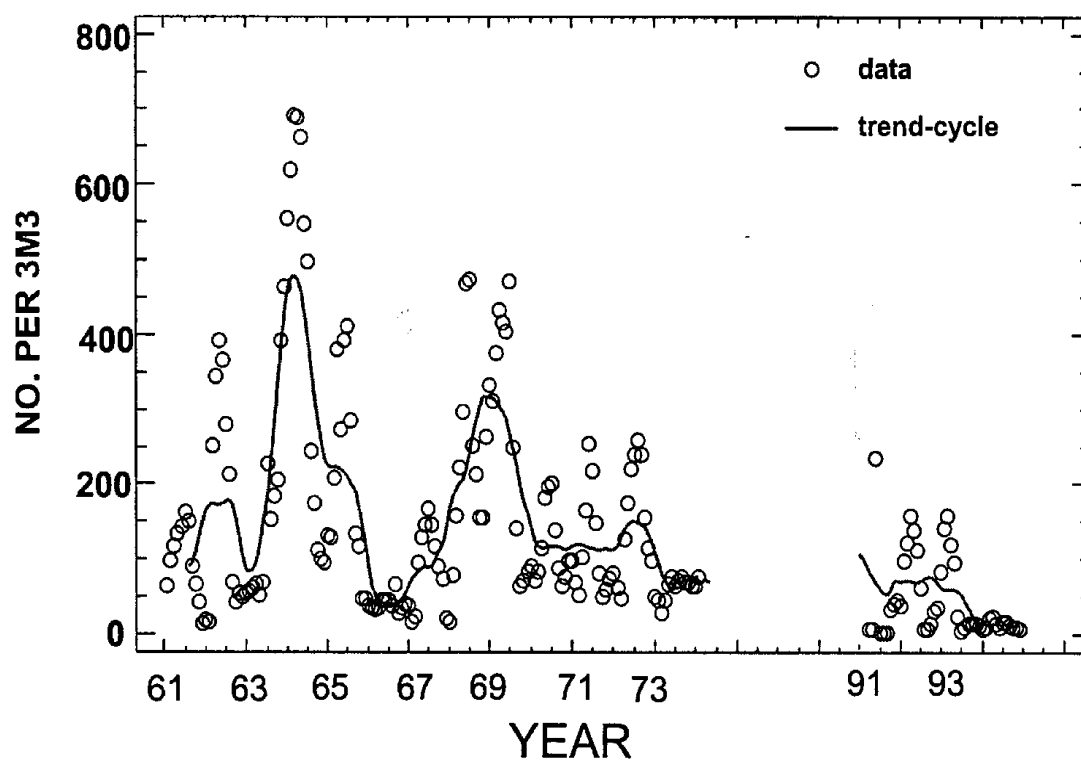


Figure 3.8.2. Monthly mean abundance of *Calanus finmarchicus*, stages 1-4 and trend cycle calculated from seasonal decomposition analyses. Data are based on Scotian Shelf CPR sampling.

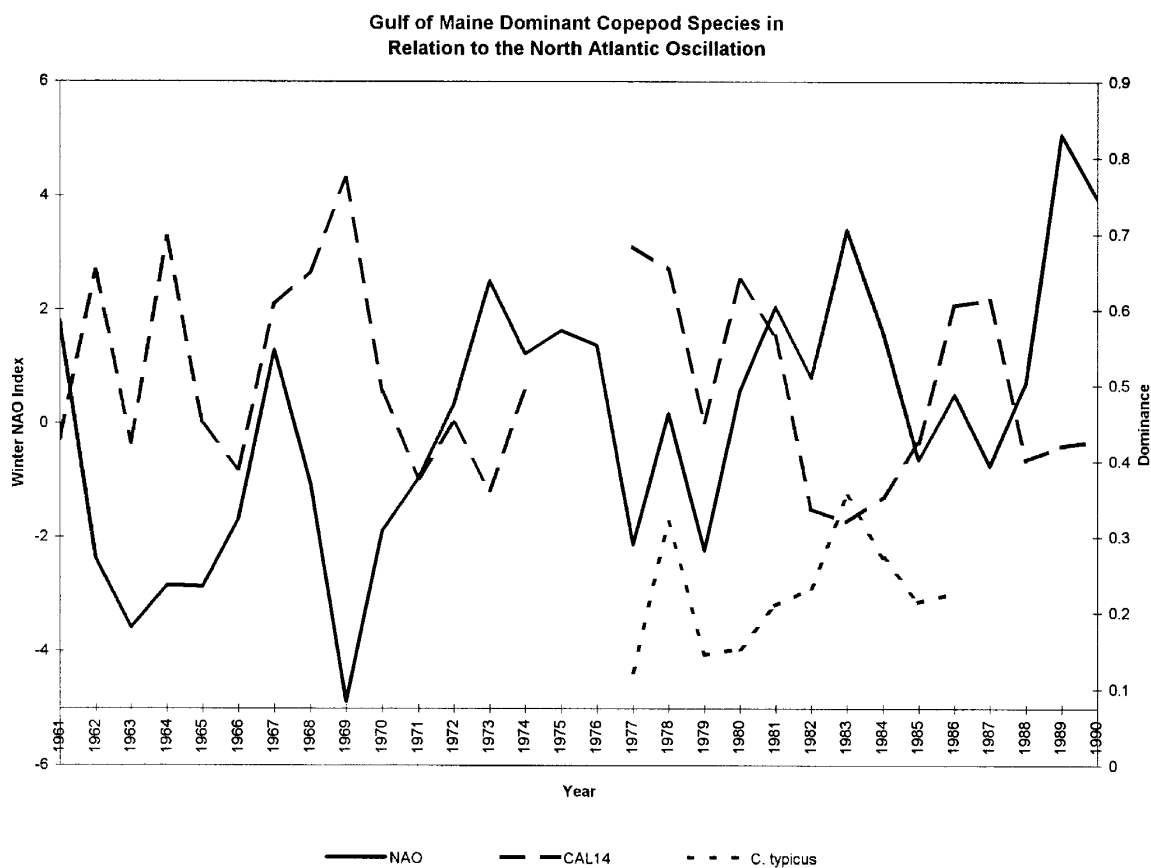


Figure 3.9. Trends in copepod species dominance vs. the winter NAO index, 1961–1990. Plankton data are from the NOAA/NEFSC CPR survey.

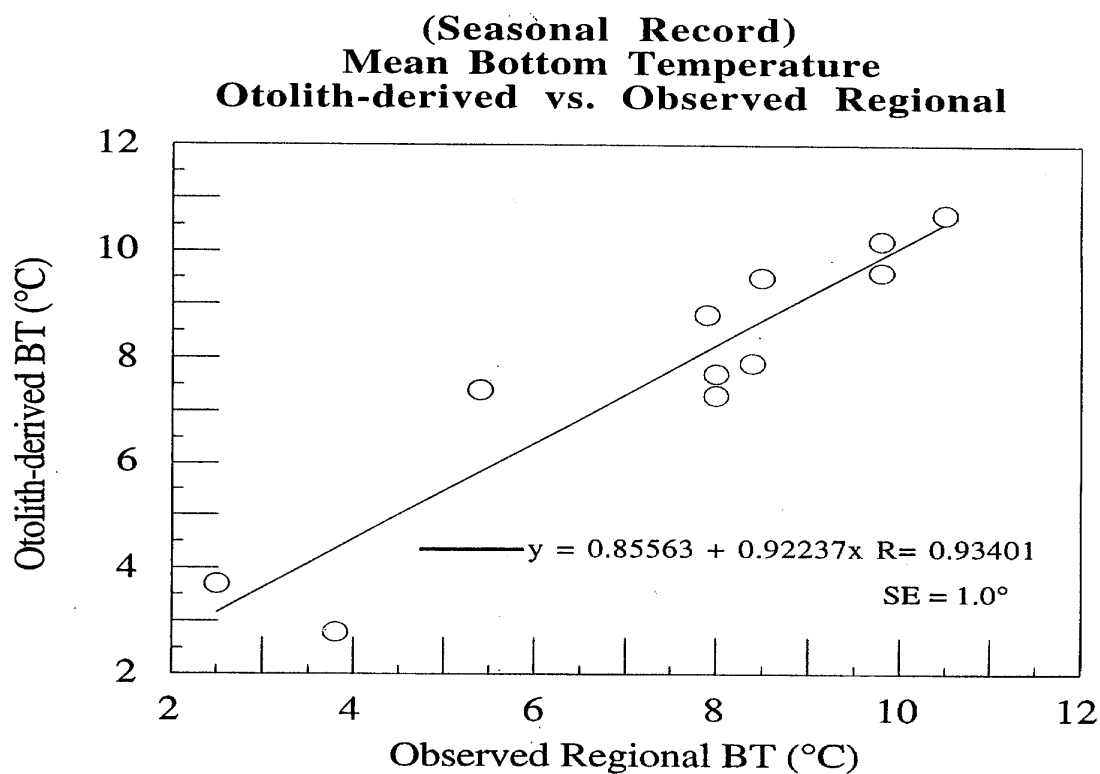


Figure 3.12.1. Relationship between observed and otolith-derived mean bottom water temperatures from Atlantic cod, based on seasonal sampling.

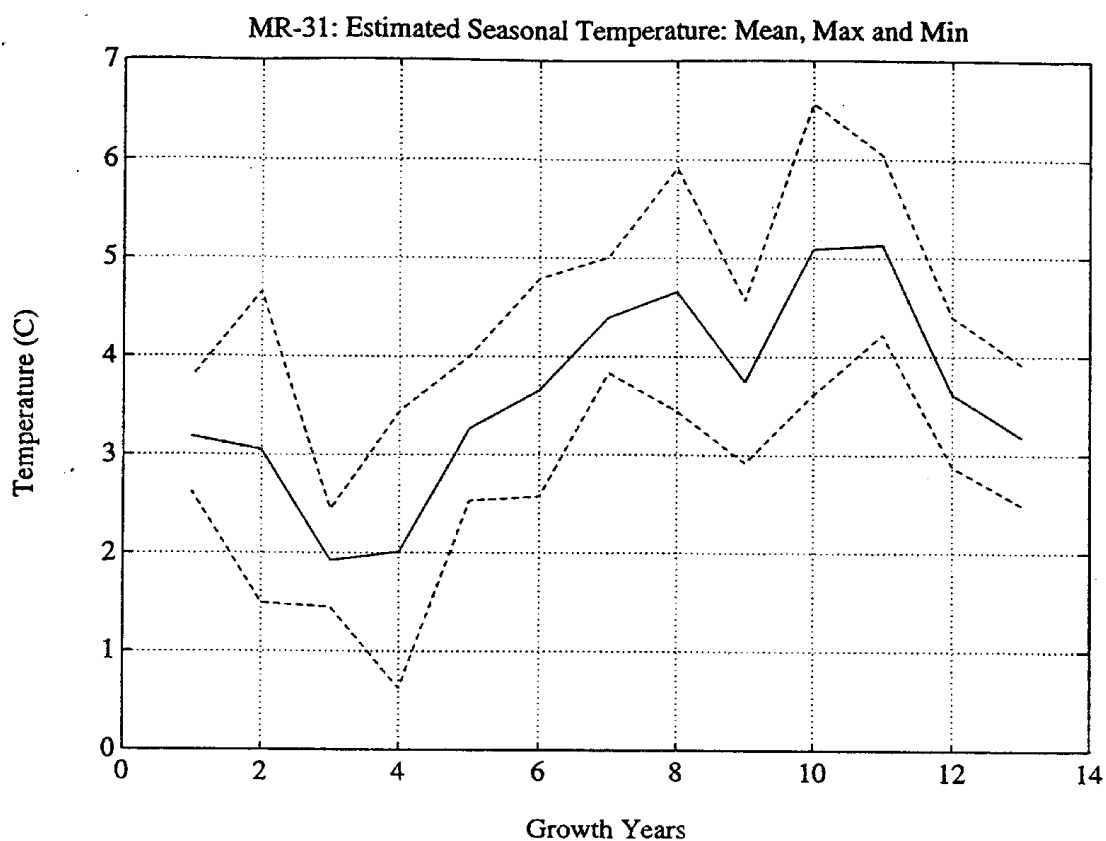


Figure 3.12.2 Seasonal bottom temperature (BT) record vs. growth year for Barents Sea cod, based on temperatures derived from oxygen isotope ratios. Solid line is the annual mean, upper and lower dashed lines are seasonal maxima and minima. First and last years are usually only partial seasonal records.

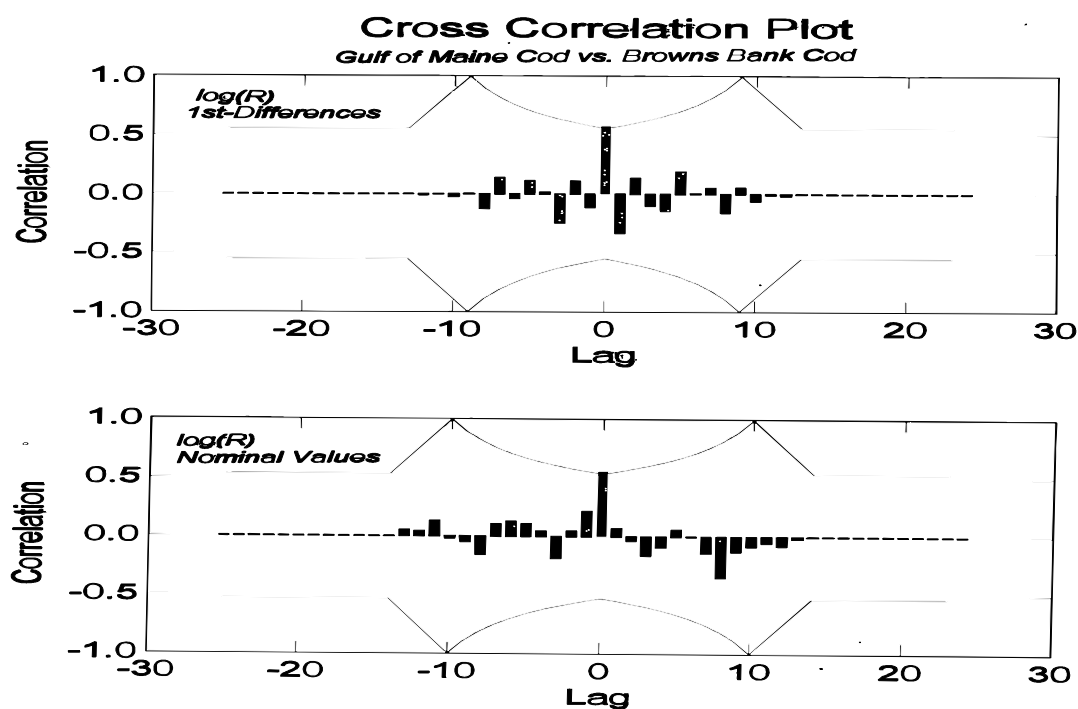


Figure 3.13.1. Tests of time series cross-correlations between Gulf of Maine and Browns Bank cod log(recruitment). Data are from VPA, age 1, and are 1st-differenced (upper) and nominal (lower). If bars extend beyond solid lines, the lag is statistically significant.

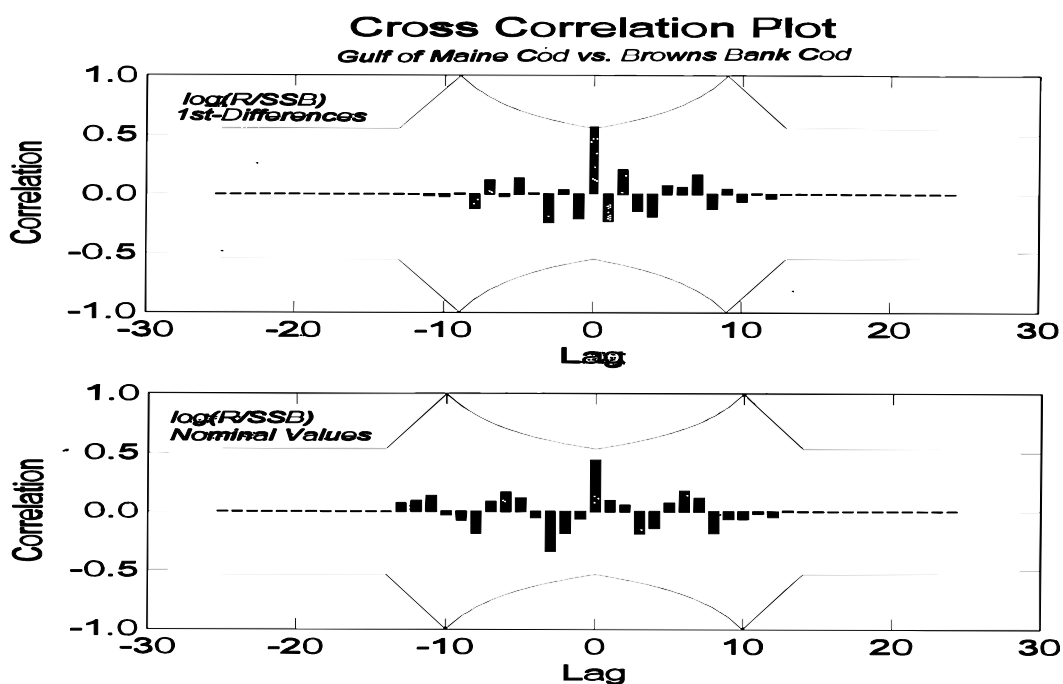


Figure 3.13.2. Tests of time series cross-correlations between Gulf of Maine and Browns Bank cod log(R/SSB). Data are from VPA, age 1, and are 1st-differenced (upper) and nominal (lower). If bars extend beyond solid lines, the lag is statistically significant.

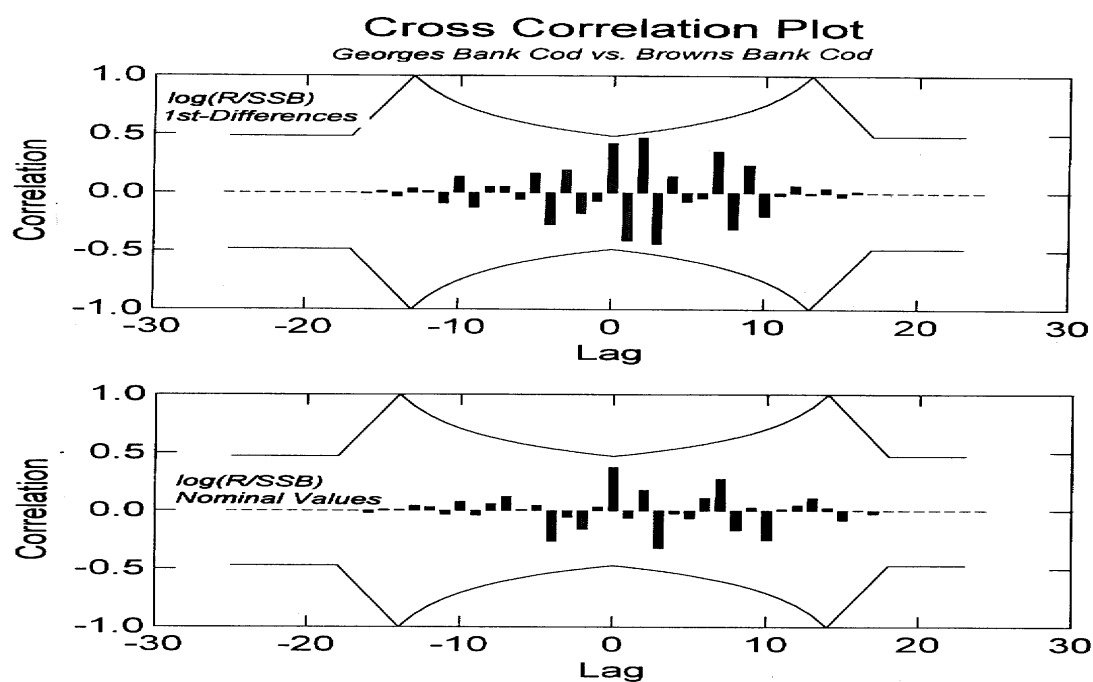


Figure 3.12.3. Tests of time series cross-correlations between Georges Bank and Browns Bank cod $\log(R/SSB)$. Data are from VPA, age 1, and are 1st-differenced (upper) and nominal (lower). If bars extend beyond solid lines, the lag is statistically significant.

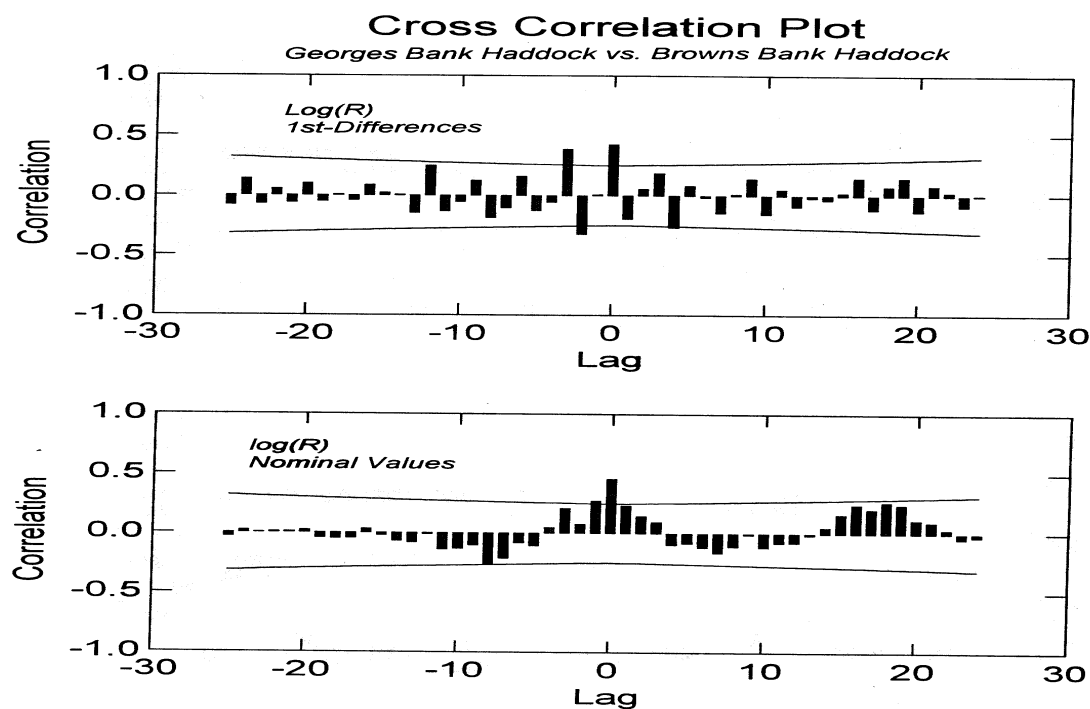


Figure 3.13.4. Tests of time series cross-correlations between Georges Bank and Browns Bank haddock $\log(\text{recruitment})$. Data are from VPA, age 1, and are 1st-differenced (upper) and nominal (lower). If bars extend beyond solid lines, the lag is statistically significant.

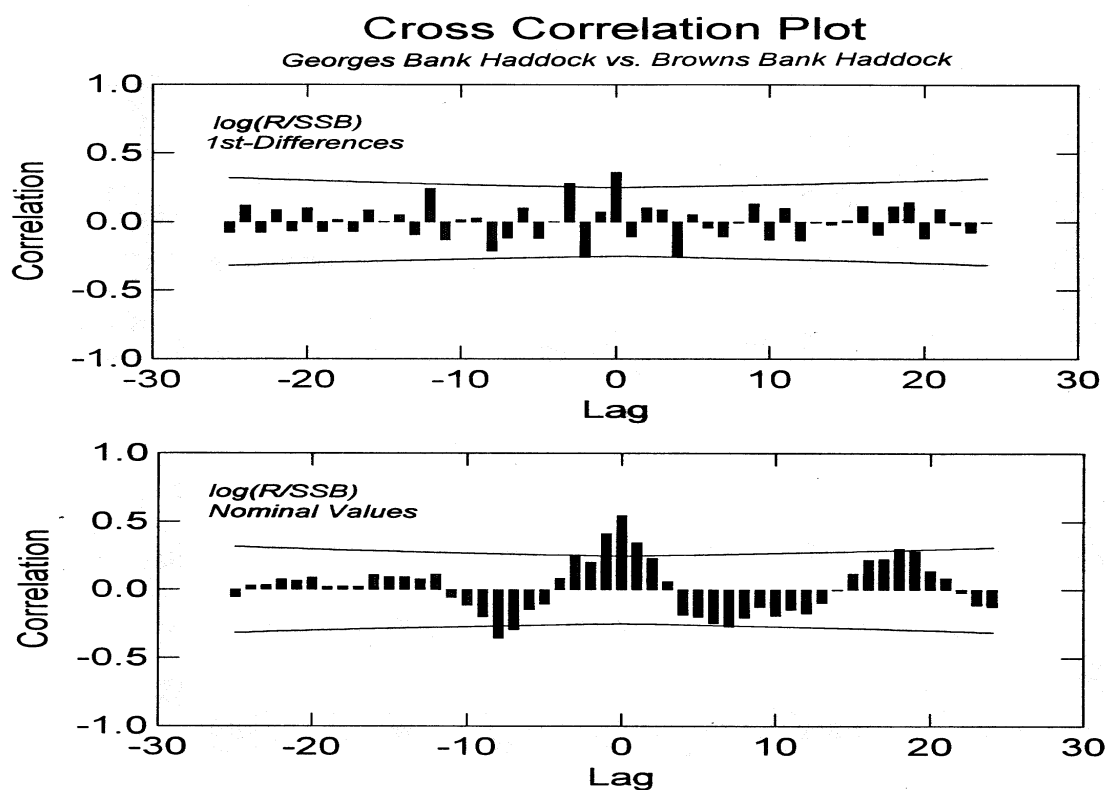


Figure 3.13.5. Tests of time series cross-correlations between Georges Bank and Browns Bank haddock $\log(R/SSB)$. Data are from VPA, age 1, and are 1st-differenced (upper) and nominal (lower). If bars extend beyond solid lines, the lag is statistically significant.

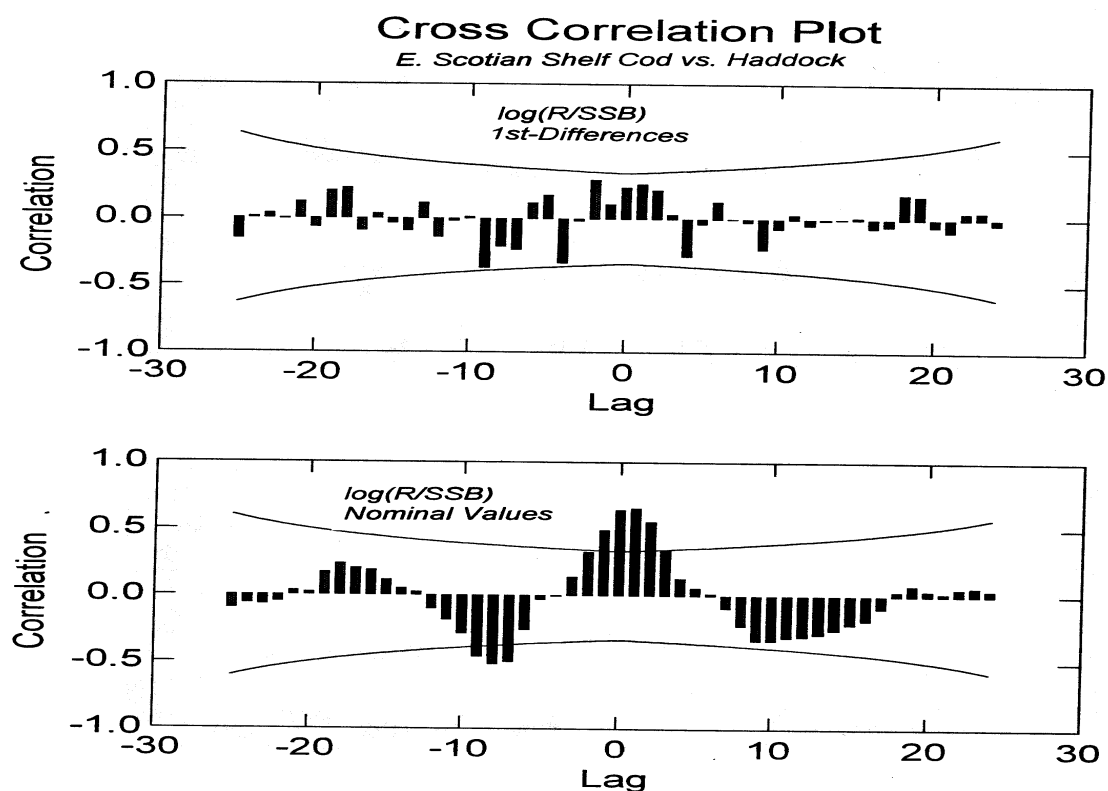


Figure 3.13.6. Tests of time series cross-correlations between E. Scotian Shelf cod vs. haddock $\log(R/SSB)$. Data are from VPA, age 1, and are 1st-differenced (upper) and nominal (lower). If bars extend beyond solid lines, the lag is statistically significant.

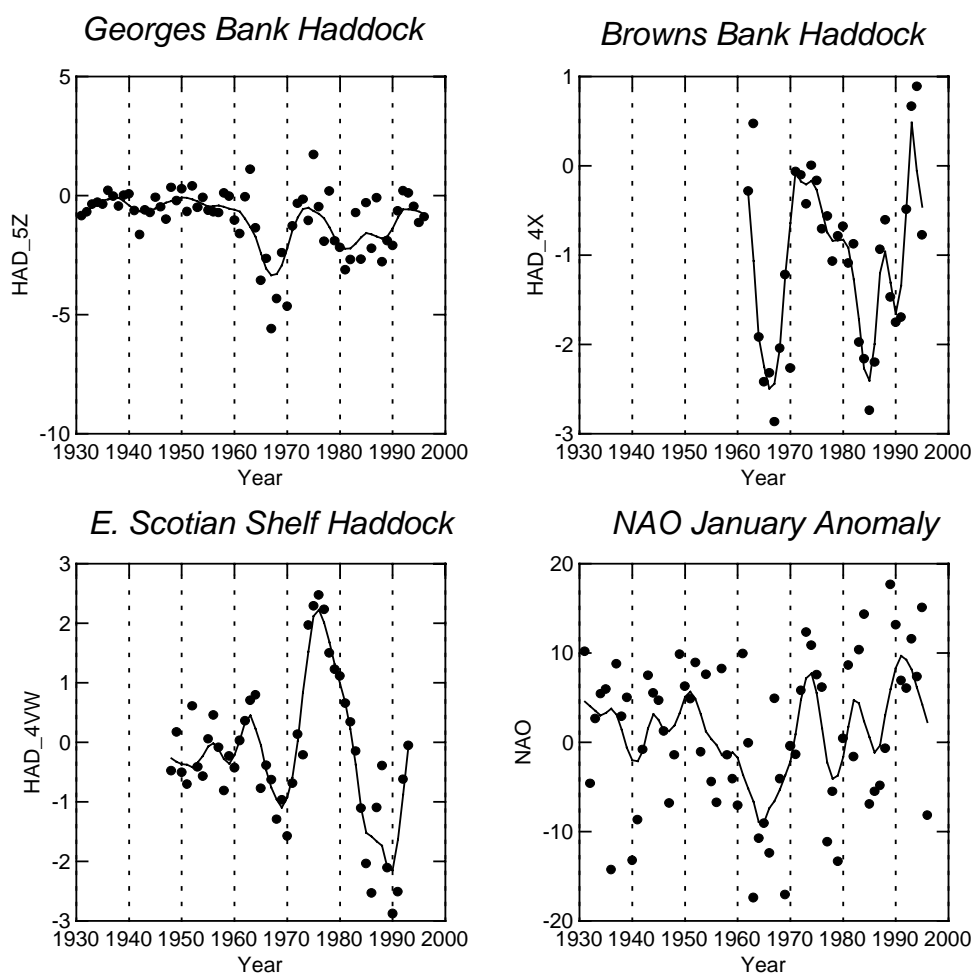


Figure 3.13.7. Trends in haddock recruitment survival [$\log(R/SSB)$], vs. January NAO anomalies, 1931-1997. A LOWESS smoother (tension=0.15) is fitted to the data.

4 Comparison of the processes which appear to govern interannual variability in gadoid recruitment on Georges Bank and in other areas of the North Atlantic

4.1 Overview

Correlations between gadoid catches, recruitment and survival during early life are described in Section 1.3. The correlations may arise because the same processes and forcing affect stocks in several areas and/or because there is exchange of fish between them.

The physical regime of the Scotian Shelf, Georges Bank and the Gulf of Maine differs considerably from that of the eastern North Atlantic. One way in which this is expressed is in the latitudinal compression of SST isotherms as one moves from east to west (Figure 4). The spatial (including depth) and temporal differences in temperature in the Scotian Shelf-Georges Bank area of the northwest Atlantic are greater than those occurring in the NE Atlantic, as are the differences in salinity. Temperature and salinity are strongly influenced by the cold, fresh currents flowing south and west, whereas in other parts of the North Atlantic surface heat flux has a major effect. One consequence of this is that interannual variability in temperature tends to be greater at depth than near the surface in this part of the NW Atlantic.

Given the greater interannual range and variability of temperature, salinity and other factors (e.g., nitrate) in the NW Atlantic, one might expect increased variability in biological indicators, such as recruitment, but this does not appear to be the case. The group discussed a number of processes which definitely or possibly govern interannual variability in recruitment in other areas of the North Atlantic and which may also be important for Georges Bank and the Scotian Shelf.

4.1.1 The Barents Sea

Results from the Barents Sea show that the recruitment in warmer years for both cod and haddock is 2.5-3 times as high as in colder years for the period 1965–1992 (Ottersen *et al.*, 1994), but only 1.5 for the period 1943–1992. One explanation for this development is the large change in the age structure of the Arcto-Norwegian cod stock over the past 40 years and the following factors may be of importance (Ottersen *et al.*, 1994):

- the influence of temperature on recruitment seems to be more pronounced when the spawning stock is small
- the age composition of the spawning stock has changed and now depends to a large degree on one or two dominant year classes
- the abundance of older cod is reduced considerably. Younger fish tend to have a shorter spawning period than older fish (Hutchings and Myers 1993), and the first time spawners produce eggs with a narrower

range of specific gravity and hence depth distribution than repeat spawners, thus resulting in less horizontal dispersion (Kjesbu *et al.*, 1992).

These changed properties of the stock cause increased sensitivity to environmental fluctuations, resulting in greater differences in recruitment between warm and cold years.

4.1.2 Warm end of the range of distribution

The presentation by Benjamin Planque looked at the effects of temperature on recruitment of cod stocks at the warm limits of the range and showed that recruitment in the Irish Sea is higher at low temperatures, as expected. For Georges Bank this effect is not obvious, but it would be useful to explore the available data on distribution at the warm end of the range on both sides of the Atlantic in order to try to detect thermal effects. Experimental results published in the 1930s (Bennett 1939) show that hatch rates of cod eggs decrease rapidly at temperatures above 10°C.

4.1.3 Spatial variation in the timing of cod spawning in the western North Atlantic

There is evidence that supports the hypothesis that the timing of cod spawning in coastal seas located around the British Isles and around Nova Scotia varies spatially and may be related to spatial variation in the timing of the spring bloom (Brander 1994, Brander and Hurley 1992). Ichthyoplankton data collected during the MARMAP surveys (1977–1987) show peaks in the abundance of cod larvae over Georges Bank, Nantucket Shoals, the western Gulf of Maine and off eastern Long Island (Morse 1994). A Gaussian curve fitted to mean abundances of <6-mm cod larvae from all MARMAP survey data on Georges Bank shows a peak on 16 April (yearday 107) approximately 3-months prior to the period of maximum water column density stratification as defined by the difference between surface and bottom water density (Bisagni 1992; Morse *et al.*, 1994). However the mean date for the onset of the earliest “transient” density stratification over southern Georges Bank, computed for an 11-year period (1985–1995) using a simple 1-dimensional potential energy anomaly model (Bisagni, in-preparation), occurs on yearday 103. Based on this, we suggest that the timing of peak abundances of cod eggs and larvae for the four stock locations be compared with the timing of the onset of stratification and primary production. This requires a consistent procedure for defining the production curves

for ichthyoplankton, phytoplankton and (zooplankton) food items.

4.1.4 Retention and dispersion

The early life history of cod stocks throughout the North Atlantic includes numerous examples of dispersion and retention and both are believed to be important in bringing about the survival of eggs and larvae. Whether spawning takes place in a dispersive or a retentive physical environment is probably related to the geography of survival conditions (i.e., food production; predator distribution; other unfavourable conditions such as high temperature and low salinity; suitable settlement substrate).

A comparison between the area occupied by spawning cod on Georges Bank and in the Vestfjord (NE Arctic cod) is instructive. The latter has a spawning biomass at least an order of magnitude greater than the Georges Bank stock, but the spawning area is considerably smaller. Although eggs and larvae may remain within the Vestfjord for some time (depending on when meteorological conditions flush them out), they are eventually dispersed in the Norwegian coastal current. If they remained within the Vestfjord then there would presumably be considerable density dependent mortality. The co-occurrence of coastal cod and NE Arctic cod in the Vestfjord area at the same time for spawning suggests that separate retention areas are not necessary in order to maintain a degree of stock separation (there is recent evidence that their love songs may be different).

4.1.5 River outflow

In Norway, landings of cod have been documented to be correlated with river outflow. The causal relationship may be due to trophodynamical teleconnections between the freshwater outflow regions and the regions of cod year class establishment (Skreslet 1997).

In the North American Atlantic waters, Sutcliffe *et al.* (1977) reported correlations between outflow from the Gulf of St. Lawrence (termed RIVSUM) and landings of some fish and shellfish species in the Gulf of Maine and adjacent regions. This relationship has not held up over time (Section 3.2). However, the anthropogenic regulation of the seasonality of river runoff has not been duly considered, although the St Lawrence has had some form of regulation of flow since the record began in 1914. More sophisticated data and analyses could be applied with special reference to runoff during the neritic planktonic production season.

To test the connection between zooplankton production and cod larval survival, habitats where zooplankton abundance is a proxy for the production should be identified and sampled for time series data acquisition and analysis. To test the validity of numerical models developed to simulate trophodynamic telecommunication of climatic forcing to cod population processes, it seems

appropriate to apply the models in different population systems, on both sides of the Atlantic.

4.2 Studies of factors influencing recruitment of cod in the Baltic Sea

Mike St. John

Results from the Baltic Sea have identified that variability in survival success of a year class is the result of processes acting primarily during the egg and larval stages. Mechanisms acting on egg survival have been identified as the availability of suitable habitat for development at present only existing in the Bornholm Basin as well as predation by clupeids. During the larval stage, processes such as feeding success and transport have been identified to influence larval survival probability. A prolonged spawning period has been identified for cod in the Baltic with repeat spawners exhibiting an extended spawning period relative to first time spawners. Repeat spawners have also been identified to produce larvae of greater size and viability. Hence, the potential exists for eggs and larvae of differing quality to be exposed to varying environmental and predation scenarios due to:

- a) intra-annual variation in oxygen conditions at the depth of egg development;
- b) variations in predation on developing eggs by sprat and herring;
- c) temporally varying food environment (i.e., from the onset of the spring bloom to the fall bloom);
- d) a spatially varying food environment;
- e) varying larval transport.

In order to resolve the importance of these processes on recruitment success, researchers utilised survivor characteristics (age of survivors, otolith hatch check size, and otolith growth rates) coupled with environmental data and model simulations to identify:

- a) environmentally influenced windows of survival as well as;
- b) the attributes of individuals exhibiting enhanced survival probability.

This approach identified two processes in particular acting to influence the survival of cod larvae. First, it is clear from the characteristics of the otolith hatch check distributions of surviving larvae that the majority of survivors in marginal oxygen conditions were the result of the reproductive efforts of large females. Secondly, comparison of the temporal occurrence of larvae and the birthdate distribution of surviving juveniles identified that survival rate was higher for individuals spawned later in the spawning season in association with a period of high wind stress. Particle tracking exercises were utilised to hind cast the source of surviving juveniles.

These suggested that the larval drift period resulting in maximal survival success to be on the order of 20 days with periods of low survival success identified to be those where larvae were retained in the central Bornholm Basin. Utilising indices of wind induced transport, predation of cod eggs by clupeids, volume of water with suitable oxygen and salinity characteristics for successful development of cod eggs as well as effective spawning stock biomass a multiple regression model of cod recruitment was developed. When modelled and observed recruitment were compared a high degree of coherence was observed ($r^2 > 0.70$) with the model capturing the trend in recruitment over the period from 1976-1992.

4.3 Response of dominant copepod species to the NAO and SST on both sides of the Atlantic

Benjamin Planque

Marjorie Lambert (Section 3.9) presented a poster relating the interannual variability of *Calanus finmarchicus* and *Centropages typicus* in the Gulf of Maine which show striking similarities with results obtained in the northeast Atlantic by Fromentin and Planque (1996).

In the northeast Atlantic and the Gulf of Maine, *C. finmarchicus* is located at the southern limit of its spatial distribution which corresponds to the upper boundary in the temperature range encountered by the species. Conversely, *C. helgolandicus* in the northeast Atlantic and *C. typicus* in the Gulf of Maine are warm water species which find themselves at their lower temperature limit in these areas. The seasonal maximum of *C. finmarchicus* is attained in May (NE Atlantic) and June (GOM) whereas *C. helgolandicus* and *C. typicus* seasonal maxima are reached in September in the two regions.

On the eastern side of the Atlantic, the North Atlantic Oscillation (NAO) is associated with changes in the sea surface temperature (SST) and alterations of geostrophic wind strength and direction during winter. In the Gulf of Maine, the NAO is related to changes in wind speed and direction but not to the SST interannual variability, as suggested by work presented by Enfield and Mestas-Nunez (Section 2.9).

In the northeast Atlantic, most of the variability in *C. finmarchicus* and *C. helgolandicus* abundance can be explained by the NAO because of its combined effects on winter SST and winds in the northeast Atlantic (Fromentin and Planque 1996). The work of Marjorie Lambert suggests that both the NAO (related to winds) and winter SST signals have to be considered to explain the year-to-year changes in abundance of *C. finmarchicus* and *C. typicus* in the Gulf of Maine. The two dominant copepod species of the Gulf of Maine and northeast Atlantic display similar responses to the environment. In both cases, the combination of winter

temperature and wind account for a large part of year-to-year variability in the abundance of the two species. The extreme wind/SST situations favour either a situation where the spring copepod maximum is amplified (*C. finmarchicus*) or when the autumn maximum is increased (*C. helgolandicus*/*C. typicus*). These changes in the abundance of the two dominant species in each region and their consequences in the seasonal timing of prey availability for cod larvae suggest a large potential for match/mismatch events related to the NAO/SST changes on both sides of the North Atlantic.

4.4 Zooplankton sampling strategies for studies of the trophodynamic coupling between climate variability and fish population dynamics

Stig Skreslet

Workshops during the GLOBEC Open Science Meeting in Paris, 17–20 March 1998, and the ICES/GLOBEC Workshop on Application of Environmental Data in Stock Assessments in Bergen, 23–25 March 1998, have concluded that there is a need to understand how zooplankton production may link effects of climate variability to variation in the ecological and commercial carrying capacity of fish stocks. In the North Atlantic, the marine copepod *Calanus finmarchicus* plays such a key role in the production of North American as well as of North European cod.

Year-class strength in the northeast Arctic cod stock depends on the cod spawning stock biomass and a variety of environmental variables working on the spawning grounds at the Lofoten Islands, Norway. One of the environmental forcing factors is the production of *C. finmarchicus* as the principal prey of juvenile cod. Presence of nauplii during spring is vital to first-feeding larvae, and copepodids enter the diet as the juvenile cod grows through the summer. The instant availability of these food items to the individual cod is a function of numerous factors in local organismic systems, but the average larval year-class survival rate in the cod stock may depend on the overall *C. finmarchicus* spawning stock biomass. *C. finmarchicus* spends the winter diapause as CIV-V in principally two different kinds of wintering habitat. One is outside the Norwegian shelf break in cold Norwegian Sea deep-water, and the other is in warm Atlantic water contained in a number of deep basins on the inner shelf and in fjords.

Recruitment of *C. finmarchicus* to fjord habitats occurs by advection of coastal surface water in early autumn, followed by intermediate-water exchange between fjords and shelf, and deep inflows that replace older basin water, repeatedly throughout the winter. A larger proportion of the early recruits than of the late ones probably fall prey to predatory plankton and fish that inhabit the basins. Thus, the late recruits possibly

constitute the larger fraction of copepods that spawn in concert with NE Arctic cod.

Little is known of the *C. finmarchicus* that spend the winter below the shelf break, but there are possibly few predators in this cold organismic system. The low temperature possibly also delays the termination of the diapause, but early migrants to the epipelagic zone may be of different origin, as the copepod reproduces during summer both in the Norwegian Sea and on the Mid-Norwegian shelf. On the inner shelf, reproduction is associated with the frontal system of the Norwegian Coastal Current, peaking in July in association with maximum freshwater discharge.

Skreslet (1997) has proposed a theory on how climate may influence recruitment in the NE Arctic cod stock by its effects on freshwater outflow to Norwegian coastal

waters. It may be valid also for other North Atlantic ROFI (Regions of Freshwater Influence), like the Gulf of St. Lawrence. To study how production of *C. finmarchicus* varies with climate and how cod year-class strength is associated with copepod production, there is a need for identification of spaces and periods that represent the copepod population size on a larger scale. On small spatial scales, in wintering habitats that contain Atlantic water, predation may cause no correlation between copepod abundances at the beginning and at the end of diapause. Thus, the study of how climatic change may induce interannual variation in the cod recruitment process, by trophodynamic transfer of energy through the food web, may require study areas with low mortality during the winter. Basins that accumulate Arctic deep-water or chilled shelf water, may be sampling locations that serve such purposes.

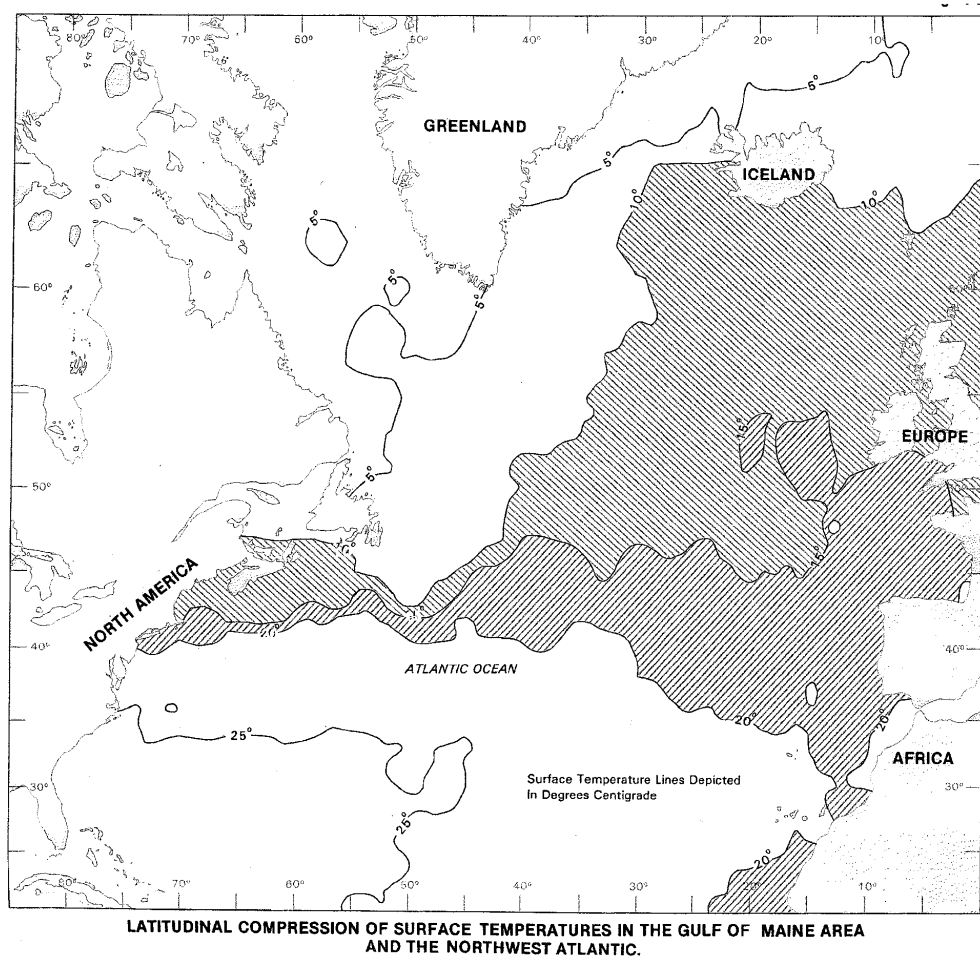


Figure 4. Sea surface temperature isotherms in the North Atlantic. Data are for the week of 13 June 1982, based on satellite AVHRC.

5 Recommendations

5.1 Recommendations for action by ICES

The BF-III workshop produced significant new information and presented biological and physical data in ways that point the direction for additional, potentially important, collaborations. The workshop recommends that one of the Terms of Reference for the next Backward Facing workshop (March 1999) should be: "Synthesize information on factors influencing gadoid recruitment in the NW Atlantic based on information presented at BF-3".

Following this and other preparations (see Recommendation below) it may be worthwhile to convene a follow-up workshop concerning the topic of gadoid recruitment in the NW Atlantic under the sponsorship of the ICES/GLOBEC Cod and Climate Program. The purpose of this additional workshop would be to continue the synthesis of factors influencing gadoid recruitment, and provide a forum for the integration of new information from studies currently underway.

New information as well as syntheses produced at this workshop will be invaluable to researchers generating new information during GLOBEC programs in the western Atlantic. Accordingly, the workshop recommends that ICES publish and disseminate the report of this workshop in the Cooperative Research Report series, under the editorship of the three co-chairs. The number of pages in the report will be c.a. 85.

Many of the recommendations for further research, including preparations for future workshops would benefit from the compilation of detailed, standardised population information for all cod stocks. The workshop recommends that the ICES/GLOBEC Coordinator should pursue all options for providing such information and should update and make available the kind of material presented in ICES Cooperative Research Report 205 (Spawning and Life History Information for North Atlantic Cod Stocks).

5.2 Recommendations for further research

5.2.1 Recommendations arising from Section 2

Determine the role of air-sea fluxes during the 1960s in the observed cooling of the waters over the Georges Bank and Southern New England regions. Studies have shown that air-sea fluxes in the 1960s could not explain all of the observed cooling of the waters on the Scotian Shelf, indicating that the cooling was also due to increased transport (and advection) of the Labrador Current and Slope waters. The relative importance of

local air-sea flux and offshore forcing is not known. Similarly, it is not known to what extent the 1960s cooling of the New England Shelf waters was part of the advective effects observed on the Scotian Shelf, or whether it was a local cooling event.

Determine the interannual variability of stratification on bank and shelf locations for the NW Atlantic shelf region. Past studies have related stratification to production and larval fish recruitment (or condition). Estimates of the onset and dissipation of stratification based on historical temperature and salinity records, combined with additional estimates based on modelling capabilities would provide an important measure of this environmental parameter.

Beginning with the 1960s time-period, storm frequency estimates need to be constructed for the (January-May) cod and haddock spawning and larval drift period. Circulation modelling studies including the effect of wind stress fields at the storm-band frequency should be undertaken to complement our current estimates of retention based on climatological wind forcing.

Efforts should be undertaken to model/hindcast the circulation and larval distribution for selected MARMAP field years, in particular, 1978 and 1987. Spring of 1978 is suggested as it had the highest year class of recruited haddock of all MARMAP years (cod was moderately high) and it could serve as the proxy for the extremely high 1963 haddock year class. There is good environmental data for the Bank for the spring of 1978, but only two larval surveys. The 1987 conditions were characterised by strong throughflow over the Georges Bank shelf-edge with possible advection of larvae into the Middle Atlantic Bight. In 1987 the recently hatched haddock larvae were collected in high percentage inside the 70m isobath on Georges Bank, but then declined in ranking with larger size classes consistent with an advective event. Cod and haddock year classes were moderate for 1987.

Analyse and model the 1997-1998 conditions (characterised by low salinity and low temperature signals) as these may be related to a low NAO index in the same manner as the 1960s time period. Present GLOBEC surveys on Georges Bank and the Scotian Shelf should provide a valuable and broad data set including hydrographic, current meter and atmospheric information.

5.2.2 Recommendations arising from Section 3

Egg and larval abundance data from the Gulf of Maine, Georges Bank and Middle Atlantic areas have been collected in the post-MARMAP period, in conjunction with routine ichthyoplankton collections and specific sampling as a part of the Georges Bank GLOBEC program. Given the importance of testing the correlations between larval abundance and year class strength, making these additional years' data available is considered a high priority, and especially prior to the proposed workshop in November of 1999.

MARMAP egg and larval abundance data should be made available for use in as spatially and temporally disaggregated a form as is necessary to support circulation modelling studies recommended above.

Given the apparent correlation in recruitment and survival during early life between cod spawning in the Gulf of Maine and Browns Bank, additional circulation modelling studies, analyses of historical ichthyoplankton data, and other biological studies, as appropriate, should be considered to resolve the issue.

Gadoid stocks of the region shared a scenario of historical overfishing, with attendant changes in the demographics of spawners (reduced age at first spawning and truncated age compositions). Because of the reliance on SSB as a control variable in managing these stocks, additional new research on the effects of maternal experience and body size on the hatching success and quality of larvae produced should be considered.

As part of demographic studies recommended above, historical information on the spawning period of various age groups of cod and haddock should be analysed to provide information on the effects of exploitation on the width of the seasonal production curve of eggs and larvae, particularly in relation to similar curves for important larval foods.

Additional environmental data, including estimates of freshwater inflows, wind stress, transport, O₂, NO₃, positions of Gulf Stream fronts, ring activity, storm events water temperatures and other parameters should be developed in a GIS format, together with appropriate biological data, to attempt a data visualization of the multiple attributes influencing recruitment survival of gadoids in the region. These efforts should be focused on when eggs and larvae are vulnerable to the effects of such mechanisms.

The effects of variation in water temperature on the growth of larvae, juveniles and adults should be investigated, particularly in relation to search volumes and prey. Data should be provided in a spatially disaggregated form. Likewise, information on the demographics of larval 'survivors' may be important in determining which environmental conditions are most likely to result in high egg and larval survival.

Areas closed in the Great South Channel and eastern portions of Georges Bank since 1994 may have altered the spatial distribution of spawners and production of eggs and larvae. Circulation modelling studies in combination with sampling of spawners and spawning products should be undertaken to assess the potential impacts of these areas on gadoid recruitment success.

Why do cod and haddock exhibit differences in annual recruitment survival and resiliency to exploitation when their spawning periods and locations are so similar? Comparative assessments of the effects of environmental and demographic variability on the synchrony (or lack thereof) in these species is an appropriate approach to this enigma.

Additional work on fish and invertebrate predators of cod and haddock eggs and larvae should include indices of predator and prey overlap, feeding frequency and diet analysis. Many of these data have been collected, but have not been analysed in a population context for the gadoid stocks.

5.2.3 Recommendations arising from Section 4

Data on patterns of distribution, migration and survival at the warm end of the range of cod should be examined from both sides of the North Atlantic, in order to detect effects of high temperatures.

The timing of peak abundances of cod eggs and larvae should be compared with the timing of the onset of stratification and primary production for all cod stocks in order to test the match-mismatch hypothesis. This requires adequate spatial resolution and a consistent procedure for defining the production curves for ichthyoplankton, phyto-plankton and (zooplankton) food items.

More sophisticated analysis of data on runoff is required to test the hypothesis that the timing of spring production depends on freshwater input.

The characteristics of survivors (age, otolith hatch check size, and otolith growth rates) coupled with environmental data and model simulations should be used to identify environmentally influenced windows of survival and the attributes of individuals exhibiting enhanced survival probability.

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Appendix 2

Listing of Climatologies

This inventory presents a simple listing of climatologies and long-term physical oceanographic and atmospheric data sets for the Scotian Shelf/Gulf of Maine/New England Shelf region. The listing is not comprehensive nor complete, but does attempt to include those data sets known to the participants at this meeting, and provide names of individuals in {} to contact for more information.

Climatology

Bunker (1976) - heat flux, surface conditions

Saunders (1977) - wind stress

University of Southampton COADS (GASC97)

{S. Josey} wind stress, heat flux. [<http://ingrid.ldeo.columbia.edu/SOURCES/.SOC/.GASC97/>]

Petrie *et al* (1996) - T/S atlas, Scotian Shelf and Gulf of Maine

3) Bedford Institute of Oceanography

On-line long-term time series data {K. Drinkwater, P. Smith}

ocean currents, Gulf Stream and shelf/slope fronts, T-S data, SST, coastal sea level, runoff, air temp, wind stress, NAO. [<http://ossci.bio.dfo.ca/science/ocean/ocean-data.html>]

Hydrographic database {K. Drinkwater, D. Gregory} 3. Canadian Environmental Buoy met data {W. Richards}

4) Brookhaven National Laboratory

a) Hydrographic database {C. Flagg}

i Atlantic Coastal Exp. (1974-85) - 3630 stations

ii SEEP (1983-84 & 1988-89) - 844 stations

iii OMP (1994-present) - 490 stations [ftp bnlpo.das.bnl.gov, anonymous/pub/beardsley/]

b) BNL tower winds: (from start of Lab, from 1960's in computer format)

5) National Marine Fisheries Service

a) Winds {J. Manning}

i NDBC environmental buoy data (1975-1995, includes 1975-1982 NLS winds)

ii Fleet Numerical model winds (1967-present)

iii NOAA/NWS National Center for Environmental Prediction weather data (1997-present)

b) Water temperature {J. Manning}

i Woods Hole NMFS dock (1960-present) b. Woods Hole WHOI dock

c) Hydrographic database {D. Mountain}

i MARMAP (1977-1987)

d) GLOBEC (1992-present)

e) CPR/T/S transect time series {J. Jossi}

i Boston-Halifax (1978-present)

ii New York-Bermuda 5. Current {J. Manning}

- 6) UMass Dartmouth/CMAST**
 - a) AVHRR-derived SST {J. Bisagni}
 - i Daily SST images (1.4 km) (1993-present) (raw, declouded)
 - ii Daily SST images (1.4 km) (1985-1996) (Pathfinder)
 - ii SST front positions (from b) (1985-1996)
 - b) Daily-averaged GB/GOM FNOC wind grid points (1985-1996)
 - c) CZCS-pigment monthly averages and climatology {J. Yoder}
- 7) United States Geological Survey**
 - a) Moored ocean measurements {B. Butman}
 - i Georges Bank site A (85 m) time series (1975-1979)
 - ii Georges Bank site K (60 m) time series (1975-1977??)
 - iii Nantucket Shoals mud patch site (60 m) time series (1975-77)
 - iv Mass Bay outfall site (1991-present)
- 8) Woods Hole Oceanographic Institution**
 - a) Lightships {S. Lentz}
 - i Nantucket Lightship (1956-1972): T,S, met
 - ii Ambrose Lightship (1956-1972): T,S, met
 - iii Georges Bank Texas Tower (1956-1962): surf T,S
 - b) Shell-derived seasonal shelf temp record {C. Weidman}
 - i Nantucket Shoals (1875-1983)
 - ii other sites (1958-1982)
 - c) Daily mean insolation (1975-present) {D. Payne}
 - d) Daily mean precipitation (1960-present) {D. Payne}
 - e) Mech. BT database (1940's-) {G. Heimerdinger}