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Recruitment, pre-recruit survival and mortality in three Newfoundland cod stocks: northern (2J3KL), southern Grand Banks (3NO) and St. Pierre Bank (3Ps)

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Abstract

Indices of recruitment (R), spawning stock biomass (SSB) and pre-recruit survival (R/SSB) were examined and compared among three Newfoundland cod stocks: northern (2J3KL); Grand Banks (3NO); and, St. Pierre Bank (3Ps). Survival generally has been lower during recent time periods compared to earlier time periods for similar levels of SSB. Survival was most strongly linked with warm temperature conditions for the Grand Banks cod stock during several pre-recruit stages and less weakly linked with the northern cod stock. There was no detectable relationship between environmental conditions and survival for the St. Pierre Bank cod stock. Estimates of mortality based on research vessel data (RV) demonstrated that mortality remained anomalously high for several years following the implementation of fishing moratoria for the northern and Grand Banks cod stocks. However, during the most recent time periods there has been a trend to decreasing mortality. Estimates of RV mortality for the St. Pierre Bank cod stock were highly variable and at times positive. It is difficult to distinguish environmental effects on survival and recruitment in the different cod stocks due to the changes in the physical environment that have varied throughout all time periods examined. Unraveling the perplexity between natural and anthropogenic factors on cod production will require new measures of the ecosystem and stock performance than are currently available for these stocks.

Résumé

Les indices du recrutement (R), de la biomasse du stock reproducteur (SSB «Spawning Stock Biomass») et de la survie prérecrutement (R/SSB) ont été examinés et comparés entre trois stocks de morues à Terre-Neuve : Nord (2J3KL); Grand Bancs (3NO); et Banc de Saint-Pierre (3Ps). En général, la survie a été plus faible durant les périodes récentes, comparativement à des périodes antérieures, selon des niveaux similaires de biomasse du stock reproducteur. La survie était plus fortement liée aux conditions de température chaude en ce qui concerne le stock de morues des Grands Bancs, au cours de plusieurs stages prérecrutement, et moins liée en ce qui concerne le stock de morues du Nord. Aucun rapport détectable n'a été établi entre les conditions environnementales et la survie en ce qui concerne le stock de morues du Banc de Saint-Pierre. Les estimations de la mortalité d'après des données des navires de recherche ont montré que la mortalité est demeurée anormalement élevée durant plusieurs années suite à l'imposition du moratoire sur les pêches en ce qui concerne les stocks de morues du Nord et des Grands Bancs. Cependant, la mortalité au cours de la période la plus récente a montré une tendance à la baisse. Les estimations de la mortalité dues aux navires de recherche pour le stock de morues du Banc de Saint-Pierre variaient fortement et étaient parfois positives. Il est difficile de différencier les effets environnementaux sur la survie et le recrutement en ce qui concerne les différents stocks de morues, en raison des changements survenus dans l'environnement physique lesquels ont varié au cours de toutes les périodes examinées. Pour faire la distinction entre les facteurs naturels et les facteurs anthropogéniques qui influencent la production de morues, il faudra faire de nouvelles mesures à partir des données sur l'écosystème et sur la performance des stocks qui sont actuellement disponibles pour ces stocks.

Introduction

The three cod stocks in Newfoundland all underwent significant declines in abundance in the late 1980's. The northern cod stock (2J3KL) and southern Grand Bank cod stock (3NO) reached historical minima by the mid-1990's (Figure 1). The St. Pierre Bank cod stock (3Ps) declined until the mid-1990's but since then has increased. Fishing moratoria were implemented for the northern cod stock in July 1992 and the southern Grand Bank cod stock in February 1994. A moratorium was implemented for the St. Pierre Bank stock 1994-1996, but since then there has been a commercial fishery.

The expectation was that the cod stocks would immediately increase in the absence of commercial fishing. However, six or more years later this has not yet happened. In contrast, these cod populations recovered quickly from declines to low abundance in the mid 1970's, when fishing mortality was reduced. Similarly, the other five cod stocks in Atlantic Canada underwent declines in the 1980's and have been slow to respond in the absence of fishing. Due to the apparent lack of recovery, the Fisheries Resource Conservation Council (FRCC) requested the Department of Fisheries and Oceans to examine the cod recruitment problem.

The Zonal Fisheries Oceanography Committee (FOC) was asked to address this problem from an Atlantic wide perspective. As part of this initiative, the FOC recommended examining similar indices among all eight cod stocks. Indices of recruitment (R), spawning stock biomass (SSB), survival (R/SSB) and modelled estimates of mortality based on research vessel survey data were examined from the most recently available assessment documents. This paper represents a summary of these indices for the three cod stocks in the Newfoundland region. To gain insight into the role of environmental factors that may affect survival, three different environmental indices were examined and related to the Newfoundland cod survival indices.

Methods

Data for recruitment (R) and spawning stock biomass (SSB) were obtained from the most recent assessment documents available from the Canadian Stock Assessment Secretariat (CSAS). An index of cod pre-recruit survival was estimated as the abundance of cod at age three divided by the spawning stock biomass that produced each year-class (R/SSB). Data were taken from the most recent Sequential Population Analysis (SPA) models, although neither the northern cod (2J3KL) or St. Pierre Bank cod (3Ps) models were considered acceptable in the recent assessments (Lilly et al. 1998, Stansbury et al. 1999, Brattey et al. 2000). Therefore, data since the 1990 year-class for the northern cod and since the 1993 year-class in the St. Pierre Bank stock are uncertain. Similarly, survival was estimated from the annual research vessel (RV) surveys. For RV data, abundance was the standardized catch rate per tow, while the RV spawning stock biomass was estimated as the multiple of the standardized catch rate, the proportion mature (%) and the weight (t).

The absence of significant directed fishing mortality on these cod stocks during the fishing moratoria provides an unique opportunity to estimate the approximate natural mortality in these populations. Instantaneous mortality was estimated using RV trawl data following the method of Chouinard et al. (1999). Mortality (Z) was estimated from an

ANCOVA allowing separate intercepts for each year-class but assuming a common slope on age. The data were restricted to year-classes that appear at least twice in the 4-yr period. The model used was:

$$\ln A_{ij} = \beta_0 + \beta_{1j} + \beta_2 X_{ij} + \varepsilon$$

where A_{ij} is the stratified mean catch per tow of year-class *j* in year *i*, β_{1j} is the intercept parameter for year-class *j*, X_{ij} is the age of year-class *j* in year *i*, and β_2 is the estimate of *Z* for the 4-yr block.

For the Northern and Grand Bank cod stocks, mortality was estimated for ages 3-7 years over four year periods, beginning in 1983 for the northern cod stock autumn survey and 1984 for the southern Grand Bank cod stock spring survey and 1990 for the autumn survey. Examination of catch curves confirmed that these ages were representatively caught by the Campelen trawl, in agreement with Godo and Walsh (1992). Therefore, we accept the Campelen-equivalent catches reported in the assessment documents. Examination of catch curves for the St. Pierre Bank RV data set indicated that ages three and four years were not representatively caught in the RV survey, producing spurious mortality results. For this stock, mortality was estimated for ages 5-9 years. Fishing mortalities for each stock were averaged for the same time/age and sampling periods, for direct comparison to the research vessel survey estimates of instantaneous mortalities.

Ocean temperature and salinity have been measured routinely at a standard hydrographic monitoring station (Station 27) located in the inshore branch of the Labrador Current on the Newfoundland Continental Shelf since 1946 (Colbourne 2000). It is located about 8 km off St. John's harbor, Newfoundland in a water depth of 176 m. This position is ideal for monitoring variations in the water properties of the inshore branch of the Labrador Current. The cold sub-zero °C water that forms the cold intermediate layer (CIL) on the continental shelf is present year around in depths from about 100 m to the bottom at 175-m depth. In recent years this station has been occupied on a regular basis, about 2-4 times per month, making it one of the most frequently monitored hydrographic stations in the Northwest Atlantic. This regular sampling permits a detailed analysis of the seasonal and interannual variability in water properties at temporal scales from months to decades. Petrie et al. 1992, showed that there is a high spatial coherence between temperature at Station 27 and across the shelf at the same depth range. However, salinity exhibits significant latitudinal and cross-shelf variability. Following standard methods, the seasonal cycles in temperature and salinity were determined by fitting least-squares regressions of the form $\cos(\omega t-\phi)$ to the annual data for the years 1961-1990. Monthly temperature and salinity anomalies, which were computed by subtracting the least squares fitted values from each observation, were then averaged to produce an annual value.

The strength of the cyclonic atmospheric circulation over the north Atlantic during the winter months to a large degree determines ocean climate variations throughout most of the year influencing such things as ice extent and duration, ocean temperatures and shelf stratification. During the winter over the north Atlantic, this circulation is dominated by a low pressure centered over Iceland and the Azores High. These systems generate northerly to westerly wind patterns in the northwest Atlantic and southwest winds in the northeast Atlantic. A convenient index representing the strength of this circulation has been termed the North Atlantic Oscillation (NAO) index and is defined as simply the difference in the winter (December-February) sea level air pressure between the Azores and Iceland (Rogers, 1984). When the NAO index is strongly negative, warm saline ocean conditions generally prevail in the northwest Atlantic and colder fresher conditions predominate in the northeast Atlantic; and vice versa when the NAO index is high positive. There are exceptions however to those expected responses, for example, during 1999 the most intense anomaly pattern was displaced towards the east over the Nordic and Barents seas thus this area saw widespread warming but the expected cooling in the northwest Atlantic did not develop.

Results

Trends in Spawning Stock Biomass and Recruitment

Spawning stock biomass has declined since the 1950's in all three Newfoundland cod stocks, the northern cod stock (2J3KL), the Grand Bank cod stock (3NO) and the St. Pierre Bank cod stock (3Ps) (Figure 1). Notable in these long-term declines were the rapid declines in the mid-1970's due to high fishing mortality before the implementation of Canada's 200 mile EEZ in January 1977. Following the reduction of fishing mortality, all three stocks rapidly recovered to higher levels during the 1980's. However, beginning in approximately 1985 biomass began to decrease in all three stocks, reaching historically low values for the northern cod and Grand Bank cod stocks in the late 1990's. Since these minima, spawning stock biomass has increased again but levels remain well below historic levels. Spawning stock biomass also declined in the St. Pierre Bank cod stock reaching a minimum in 1996. However, this minimum was not as low as that observed in the 1970's and since that time the spawning stock biomass has reached near historical highs.

Recruitment in all three cod stocks underwent long-term declines from the 1950's until the middle to late 1980's (Figure 2). By 1987 recruitment in the northern cod stock was in a steep decline. On the southern Grand Bank this rapid decline did not occur until 1990. In both stocks, recruitment has been well below historical values during the 1990's. The St. Pierre Bank stock did not experience these sharp declines in recruitment during the 1990's. In all three stocks, short term variations were superimposed on the long-term declines in recruitment where each stock demonstrated significant autocorrelation at 3-5 year time periods for most of the time series, although the lagged correlations increased with the final periods of length declines in recruitment.

Indices of Pre-Recruit Survival

Pre-recruit survival varied widely during four decades in these three cod stocks, from the 1960's through the 1990's (Figure 3). Survival was largely coherent among stocks until the 1980's. Throughout the 1960's and the 1970's, survival tended to be higher for southern Grand Bank cod compared to the other two stocks, which were similar in magnitude. Survival reached minima in 1970-71 followed by high survival in the late 1970's. Survival declined to historical minima in all three cod stocks by the late

1980's and low survival continued into the 1990's. Survival declined first for the southern Grand Bank and was then the lowest among the three stocks. Survival for the northern cod stock reached near-zero values in 1990 and 1991 before increasing again in the mid-1990's. At this time, survival estimates for the northern cod stock were calculated from extremely low levels of spawning stock biomass, that have been less than 0.25% of the historical mean since 1990.

A comparison of the pre-recruit survival index between SPA and RV estimates indicated close agreement for the Northern and Grand Bank stocks (Figure 4). In particular, the high survival index estimated from the non-accepted SPA of the northern cod stock was also reflected in the RV data, indicating that survival has been relatively high in recent years for an extremely low SSB. Survival indices for the St. Pierre Bank stock were highly variable depending on which set of RV data were used, but generally corresponded to the index estimated from the SPA data, where survival has tended to decrease in recent years.

Survival Compared to Spawning Stock Size

There was a similar response of pre-recruit survival compared to spawning stock biomass in all three stocks for year-classes produced in the late 1950's through to the late 1970's (Figure 5). As stock sizes decreased for all three stocks, survival varied within mid-ranges, declined to minimum values in the 1969-73 period, then increased to historically high values in the 1974-78 period for the Northern and St. Pierre Bank cod stocks and to second highest values for the southern Grand Bank stock. After this time, the patterns varied among stocks. In comparing survival among the three cod stocks, it is notable that survival indices were low during the 1980's and 1990's compared to earlier periods for similar stock sizes.

In the northern cod stock, survival remained relatively high for the 1979-82 year-classes before declining precipitously during the 1983-89 period for a SSB that remained relatively stable between 250,000 and 500,000 t (Figure 5). From 1990 to 1992, survival remained at historically low values near zero as SSB declined towards the origin. From 1993-1995, survival has increased to historically high levels. However, these survival indices were estimated from extremely low values of SSB and must be treated with caution.

Survival for the southern Grand Bank cod stock declined from 1979 to very low values for the 1983-1987 year-classes (Figure 5). These low levels of survival occurred for through a mid-range SSB as stock size increased from 30,000 t to 80,000 t. During this period, survival was considerably lower than all previous estimates at similar values of SSB. From 1988-1996, survival remained at extremely low values as SSB declined from 80,000 t to near zero values.

Following the historically high survival estimated for the 1978 year-class of the St. Pierre Bank cod stock, survival declined from 1979 to 1984 as SSB increased from relatively low values to mid-range values of 100,000 to 120,000 t (Figure 5). Survival remained relatively low from 1985 to 1994 as SSB declined again to approximately 40,000 t and remained low as SSB increased again to approximately 100,000 t in 1996.

Instantaneous Rate of Total Mortality

Instantaneous RV mortality increased significantly in the northern cod stock beginning with the 1989-92 period, increasing by a factor of approximately 4x during the 1990-93 and 1991-94 periods (Figure 6). Mortalities had decreased by the 1992-95 period but were still 2-3x higher than in the 1980's. However, by the 1993-96 period mortalities had dropped to ~0.28 y^{-1} and then to less than ~0.15 y^{-1} during the 1994-97 and 1995-98 periods. This trend in instantaneous mortality estimated from the research vessels survey data was mirrored by the SPA based estimates of fishing mortality (F) for these ages. The decline in mortalities during the 1990's coincided with the 1992 fishing moratorium, although there was a lag of several years before mortalities declined. For example, the 1989-92 estimate of Z included the first year of the fishing moratorium, through to the 1992-95 estimate where all four RV survey years occurred during the fishing moratorium. However, instantaneous mortality during these four periods were the highest of the entire series, peaking with the 1990-93 and 1991-94 estimates. Mortality did not decline until the 1993-96 period. This indicates that the high mortalities estimated during this period were not due to fishing, as estimated in the assessment (Lilly et al. 1999) but were due to a high level of 'natural' mortality in the absence of directed fishing effort. The decline in mortality in the middle and late 1990's occurred following the complete collapse of the northern cod stock, offshore.

Grand Bank cod had two peaks in mortality. The first occurred during the 1986-89 and 1987-90 periods, reaching a maximum of ~1.0 y^{-1} (Figure 7). This was followed by a period of lower mortalities for the 1988-91 to 1991-94 periods after which mortalities peaked at ~0.86 y^{-1} during the 1993-96 period. In both instances, mortalities increased over multi-year periods. The abrupt decline in mortalities beginning in the 1994-97 period coincides with the implementation of the fishing moratorium in February 1994. Instantaneous mortalities were very similar for spring and fall surveys except for the 1993-96 period. Estimates of fishing mortality do not closely reflect the estimate of instantaneous mortality and often were of lower magnitude. Fishing mortality systematically increased from the 1984-87 period to a peak value of ~0.69 in 1990-93. By the end of the time periods, fishing mortalities were essentially the same as estimates of instantaneous mortalities. As with the northern cod stock, there was a lag between the implementation of a fishing moratorium in 1994 and a decline in RV mortality. The first period in which the fishing moratorium would be included in the mortality estimate was the 1991-94 period, while the full effect of the moratorium would have occurred during the 1994-97 period. However, mortality increased until the 1992-96 period followed by an abrupt decline during the 1994-97 period, and further declined during the 1995-98 period. In this stock, fishing mortality did not mirror the estimate of RV mortality but systematically decreased in accordance with the timing of the fishing moratorium, beginning with the 1991-94 period. Therefore, it appears that a high level of 'natural' mortality occurred in this stock up to some time in the mid-1990's. A similar increase in RV mortality greater than fishing mortality estimates occurred in the late 1980's.

Instantaneous RV mortality estimates for the St. Pierre Bank cod stock varied wildly over the entire survey period, 1983-1999 (Figure 8). There was a single large catch during the 1995 spring survey which has a significant effect on the mortality estimates. If this set was included with the annual survey estimates then mortality estimates for the 1992-95 period were positive. Removing this single tow from the 1995 survey removed this artifact but a positive estimate then appeared for the 1995-98 period. It is noteworthy that mortality never exceeded –0.8 y^{-1}, as it did for both the Northern and Grand Bank stocks. For the St. Pierre Bank stock, both instantaneous and fishing mortality estimates decreased coincident with the fishing moratorium implemented 1994-96, then increased again with an increase in the Canadian TAC to 8,400 t in 1997, 16,800 t in 1998 and 25,300 t in 1999 (FRCC 2000), plus an additional 15% quota to France. The low RV mortalities estimated for the final period, 1996-99, are unexpected given the increase in fishing activity in recent years.

Environmental Conditions

The NAO index data series extends continuously from 1898 to the present. The time series is characterized by large amplitude fluctuations up to ±15 mb with periods ranging from annual to 20-year cycles (Fig. 9). From the early 1900s up to the mid-1960s the pressure fields have varied at approximately 20-year time periods and at decadal time periods from the early 1970s to the late 1990s. Superimposed on these oscillations was a long-term decline in the index from 1898 to the mid-1960s and since then an increasing trend is evident. Some of the annual variations are no doubt due to spatial variability in the winter atmospheric pressure fields, as was the case during 1999. There were significant negative correlations between the NAO index and temperature and salinity measured off Newfoundland, for the period 1950-1999 when temperature and salinity were monitored. Temperature correlated with the NAO most significantly for the year of measurement (r=-0.42, P=0.0057, n=41) but also correlated significantly at lags of up to three years. Salinity was only correlated with the NAO for the year of measurement (r=-0.30, P=0.0536, n=41).

During the first half of the 20th century the NAO index was above average, indicating conditions tended to be those associated with cold water. During the 1960's, the NAO index declined significantly to historically low values, which were associated with warm water conditions off Newfoundland (Figure 9). However, since the 1970's the NAO index has increased to above normal conditions associated with cold water conditions. The peak values of the NAO index measured in the early 1990's was associated with the coldest temperatures measured off Newfoundland since continuous records began in 1950. During the last 100 years, the warm water conditions that occurred the 1950's and 1960's appear to be anomalous. It is notable that during this period record landings of the northern cod occurred (Figure 9).

Temperature and salinity on the inner Newfoundland Shelf (180 m) have varied from periods of warm-salty conditions prior to the 1970s, cold-fresh conditions during the early 1970s and early 1980s to cold-salty conditions during the mid-to-late 1980s and most recently, cold-fresh conditions during the first half of the 1990s (Figure 10). From the 1950's to the mid-1990s temperature and salinity varied somewhat in phase, although the phase difference changed over time. The salinity cycle preceded the temperature cycle by approximately five years in the late 1960s and decreased to 1-2 years from the late 1970s to mid-1990s. During the 1990s, however, while both cycles were more or less in phase the amplitudes were quite different. During 1985 both temperature and salinity began to increase, however the temperature never recovered to above normal values until the latter half of the 1990s whereas salinity increased to above normal values during 1988 but then fell to below normal values during the early 1990s. These fresher-than-normal conditions have continued into 1999 while temperatures have continued to increase and have remained above the 1961-1990 mean conditions (Colbourne 2000).

Comparison of the temperature and salinity (TS) surface for the period 1950-1999 demonstrates there are two TS polygons: one characterized by high temperatures and both high and low salinities; and a second characterized by low temperatures and low salinities (Figure 11). In addition, examination of the time trends of the TS data demonstrates periods of relative stability in the high TS polygon and periods of rapid change where TS excursions from the high polygon were abrupt and where TS values changed significantly within the low TS polygon. These excursions are demonstrated for three periods: 1969-1975; 1982-1986; and 1990-1996 (Figure 11). We regard these periods as poor environmental periods characterized by low temperatures and salinities that changed rapidly among years. It is noteworthy that the longest period of stable water properties (TS) occurred over the 20-year period from 1950-1969, a time period of decreasing NAO towards a warmer environment and a period of record landings of northern cod. Since that time, TS conditions have oscillated between the high and low TS polygons approximately every five years (range 3-8 y).

Survival indices for the three Newfoundland cod stocks tended to follow the temperature cycle off Newfoundland, where survival increased with warmer temperatures (Figure 12). However, trends in the survival indices tended to precede the temperature cycle. In the northern cod the most significant correlations with survival occurred at lags in the temperature cycle of 1-2 years (Table 1). There were no significant correlations between survival and salinity and the only significant correlation with the NAO was at a lag of two years. In the southern Grand Bank cod survival was correlated with temperature at all lagged periods, where the most significant correlations occurred at lags of two years or more (Table 1). Salinity was significantly correlated for the year of birth as well as at a lag of one year while the NAO index was correlated at lags of 0-4 years. In the St. Pierre Bank cod there were no significant correlations between survival and any of the environmental indices (Table 1).

Discussion

Abundance estimated by SPA models are notoriously unstable for the most recent years estimated by the models, where the abundance at age of the recent year-classes tends to be over-estimated (Rivard and Foy 1987). While RV data are free of this alias, annual trawl surveys can have year effects which bias year to year estimates of abundance across all ages. However, it is apparent that the SPA and RV estimates of survival are essentially in agreement. This is of particular importance for the northern cod stock, where the SPA model has not been considered reliable in the absence of a commercial fishery since 1992. However, we caution about regarding the recently high estimates of survival for the northern cod stock as being realistic. The SSB for this stock from the assessment data is <0.25% of the historical mean. In addition, the population estimates are only for the offshore population. Currently, the inshore contains relatively large spawning components compared to the offshore where there is essentially none. In addition, juvenile cod are known to occur primarily within the inshore area at young ages and to migrate onto the adjacent offshore area at ages three and older (Dalley and Anderson 1997, Anderson and Gregory 2000). Therefore, the very high survival estimates in recent years may have occurred due to the migration of juvenile cod spawned inshore onto the adjacent offshore area. Until the inshore area is properly assessed in terms of its spawning biomass and juvenile cod abundance, it will be difficult to interpret offshore data in terms of abundance and survival.

Survival is expected to vary in relation to spawning stock abundance, under the assumption of compensatory population dynamics (Odum 1971). At high levels of abundance survival is expected to decrease, or reach a maximum value at some middle range of abundance and remain approximately constant. As population abundance decreases, survival is expected to increase. This was the response observed in the survival indices for all three cod stocks in the late 1970's. At very low levels of abundance, depensatory mechanisms may intervene to decrease survival, ultimately driving the population to extinction (Odum 1971). Depensation appears to have occurred in the Northern and Grand Bank cod stocks in the 1990's, where survival has been extremely low as the SSB has moved towards zero.

The degree to which the current low levels of survival in these stocks is a function of very low SSB and possible compensatory mechanisms, such as the Allee principle, versus poor environmental conditions is difficult to determine. However, there is some indication that poor, or different, environmental conditions have played a role. This is particularly evident for the St. Pierre Bank cod stock where survival has been low in recent years compared to previous periods at comparable SSB's. In addition, the low SSB's for the St. Pierre Bank cod are still relatively high in a historical sense compared that of either the Northern or Grand Bank cod. Therefore, it is difficult to attribute the low survival during the early 1990's to low SSB. This is also somewhat evident for the Northern and Grand Bank cod where survival was much higher at comparable SSB's in the late 1970's.

The lag in a reduction of mortality in the northern cod stock following the implementation of the fishing moratoria was not expected. This indicates that significant sources of mortality continued for some period of time following the July 1992 moratorium. However, since 1993 the modelled mortality coefficients indicate mortalities less than 0.2 per year. Year to year estimates of mortality in the northern cod remained relatively high in recent years (Lilly et al. 1999), although these estimates have shown a decreasing trend in recent years. Together, these data indicate that the trend for the northern cod was towards lower mortalities in the offshore for cod ages 3-7 in recent years. For southern Grand Bank cod, the trend to lower mortalities began with the 1991-94 period and has continued through to the most recent period, based on the autumn RV data. The reason for the higher variability and the different trend in mortality based on spring RV data is not known. The spring data indicate that mortality increased and remained extremely high up to the 1993-96 period. However, there was an abrupt drop in mortality beginning with the 1994-97 spring RV period, consistent with a closed fishery. We have not examined possible sources of mortality that may have resulted from ongoing fishing following the moratoria, such as bycatch which may have contributed to higher than expected mortalities. Otherwise, the anomalously high mortalities estimated from the RV data would reflect anomalously high natural mortality in the absence of fishing.

The high degree of variability in the estimates of instantaneous mortalities for the St. Pierre Bank cod stock is problematic, where some estimates were actually positive. In addition, the failure of the survey to reliably estimate the abundance of age three and four year old cod indicates that the survey fails to capture recruiting year-classes until they reach at least age five. This contrasts with RV surveys for the Northern and Grand Bank cod stocks. These observations suggest two possible mechanisms. In the first instance, it appears that the 3Ps spring survey does not sample the areas where young cod < 5 years of age occur. Second, it appears that cod may migrate into and out of the survey area among years.

When a change in an environmental index lags that in survival, it indicates that any effect operates after the first year of life, whereas a relationship during the year in which the year-class was formed indicates a relationship may have occurred during the egg and larval drift stages. Comparison of survival and environmental indices indicated that the most profound effect was on the southern Grand Bank cod. In particular, warm and salty conditions favour survival in this stock. The significant correlations for the first and second years of life indicate that conditions affecting survival operate on egg, larval and juvenile stages prior to recruitment. In the northern cod, the relationship between survival and the environment was only manifest with temperature at lags of one and two years. This indicates that there was no apparent relationship of the environment on egg and larval survival, but that the effect was more important on juvenile cod one and two years old. As with southern Grand Bank cod, warmer conditions favored survival. In the St. Pierre Bank cod the lack of any association between pre-recruit survival and large scale environmental forcing stands in contrast to the other two stocks. It indicates that there is no direct relationship between the environment and survival. However, the coherence in survival among the three stocks for most of the time series indicates a similar survival response occurred. Examination of the data indicates that the coherence in survival among the three stocks breaks down between the St. Pierre Bank cod and the Northern and Grand Bank cod in recent years. Since the mid-1980's survival has tended to increase in St. Pierre Bank cod, while it decreased in the other two stocks.

Water column temperatures on the inner Newfoundland Shelf have recently undergone both the longest period of below normal conditions (1982-1995) and have reached the lowest values ever recorded (>4°C below normal during the spring of 1991) in this region. Historically, TS conditions usually varied from periods of warm-salty conditions to periods of cold-fresher conditions. However within the recent prolong period of below normal temperatures, salinities have ranged from saltier to fresher than normal conditions, disrupting the historical relationship. Recent data from 1999 suggest a continuation of an anomalous TS relationship, however, with warmer and fresher conditions. This may be within the normal variations in the phase between the TS cycles which as mentioned above may be directly related to recent spatial variations in the NAO anomaly patterns.

Historically the upper layer salinity on the Newfoundland Shelf reached its minimum during late September, corresponding to the arrival of spring ice-melt water from the Labrador Shelf (Myers et al. 1990). The increased ice production associated with high NAO index and subsequent melting have opposing effects on the salinity cycle, creating either positive anomalies due to salt rejection or negative anomalies from fresh melt-water. In addition, spatial variations in the location of ice formation and melt together with advection determine local anomalies. For example, increase ice formation further south on the eastern Newfoundland Shelf will generally produce positive salinity anomalies there since the melting will most likely occur further south due to advection. Recently, ice production on the Newfoundland Shelf has been below normal and with warmer than normal air temperatures ice melt occurred on the Labrador Shelf earlier in the year. This has resulted in a phase shift in the salinity cycle causing fresher than normal salinities further south, by mid-spring for example during 1999 on the Newfoundland Shelf. The non-linear dynamics causing variations in ocean temperature (which is mainly determined by the NAO and resulting wind patterns) and salinity (determined by ice conditions) have altered the normal TS relationship and shelf stratification resulting in a different ocean climate regime in this region during the 1990s. The effects of these changing conditions on primary production, nutrient supply and cod recruitment to the shelf waters remains speculative and requires much more effort as more data becomes available.

Throughout the time periods in which we have compared biological and environmental trends, it is clear that conditions continue to change. No single period in the past has been repeated in recent times. The NAO index indicates there are annual, decadal and centurial cycles that have occurred but not yet repeated. We observe the same thing with the temperature and salinity cycles that are not coherent in phase or amplitude over a 50 year period. Superimposed on the obvious non-linear dynamics of the physical environment are the dynamics of the cod stocks which have been subjected to enormous levels of fishing mortality during different periods. More observations over longer time periods may begin to resolve the interplay of environmental effects, versus fishing, on cod population dynamics and production. Alternatively, unraveling the perplexity between natural and anthropogenic factors will more likely proceed with better measures of the ecosystem and stock production. Among these, measuring dynamics earlier in the life history of cod is an obvious step in this direction.

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Table 1. Lagged correlations (yr) between cod survival indices and environmental indices. NAO - North Atlantic Oscillation. Shaded cells - P < 0.05.

	Northern Cod (2J3KL)			Grand Banks Cod (3NO)			St. Pierre Bank Cod (3Ps)		
Lag	Temperature	Salinity	NAO	Temperature	Salinity	NAO	Temperature	Salinity	NAO
0	0.147	0.002	-0.043	0.380	0.352	-0.471	-0.095	0.193	0.054
1	0.346	0.035	-0.243	0.382	0.350	-0.566	0.047	0.273	-0.039
2	0.414	0.100	-0.380	0.448	0.298	-0.563	0.073	0.053	-0.024
3	0.285	0.144	-0.251	0.444	0.252	-0.452	0.120	0.082	-0.060
4	0.259	0.151	-0.148	0.496	0.182	-0.316	0.188	0.131	-0.117
5	0.158	-0.032	0.021	0.470	0.057	-0.272	0.069	-0.109	-0.163

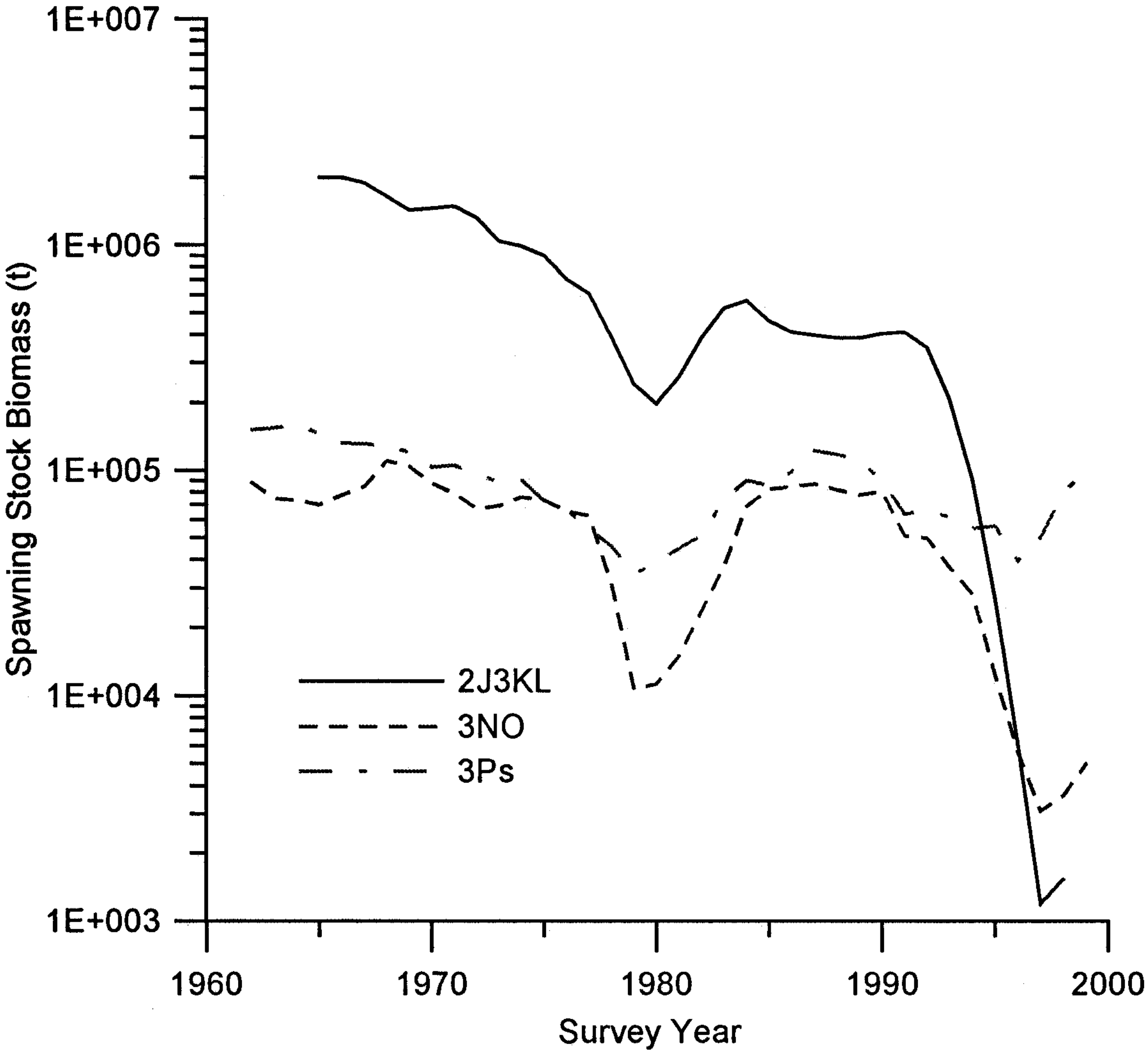


Figure 1. Spawning stock biomass (t) for northern cod (2J3KL), Grand Bank cod (3NO) and St. Pierre Bank cod (3Ps), as estimated from the most recent Sequential Population Analyses.

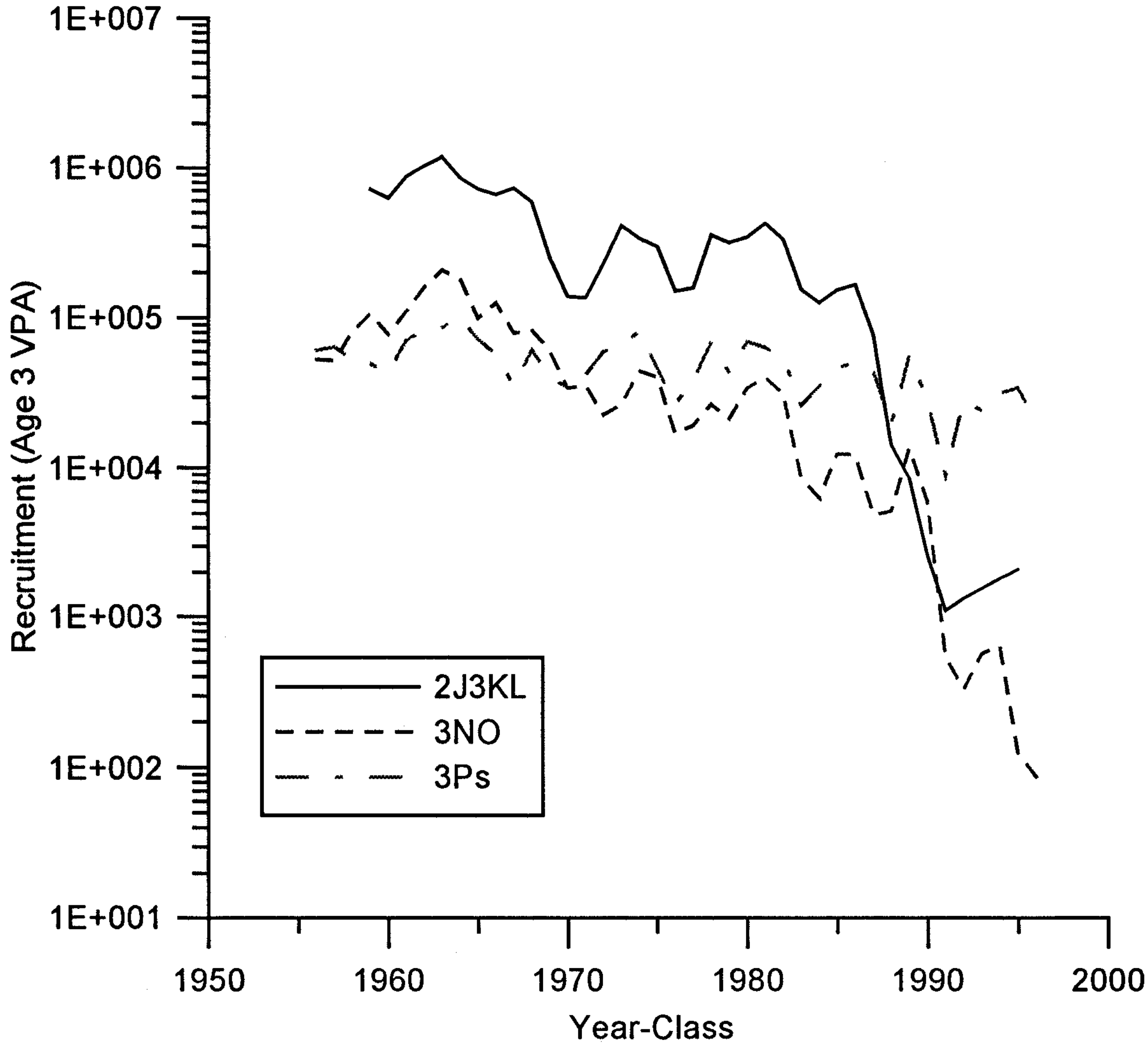


Figure 2. Recruitment in the northern cod (2J3KL), Grand Bank cod (3NO) and St. Pierre Bank cod (3Ps), as abundance estimated at age three years by Sequential Population Analyses.

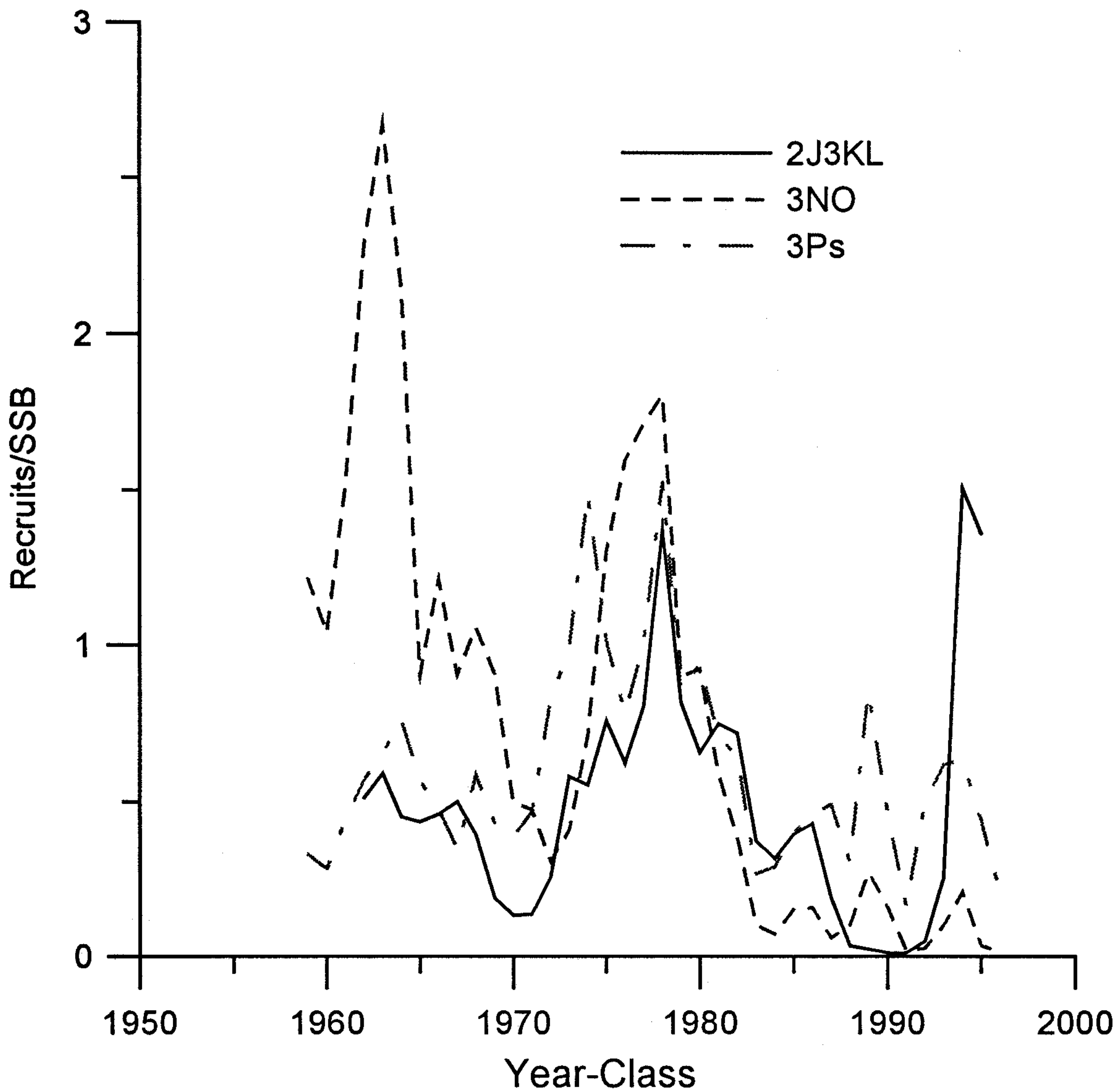
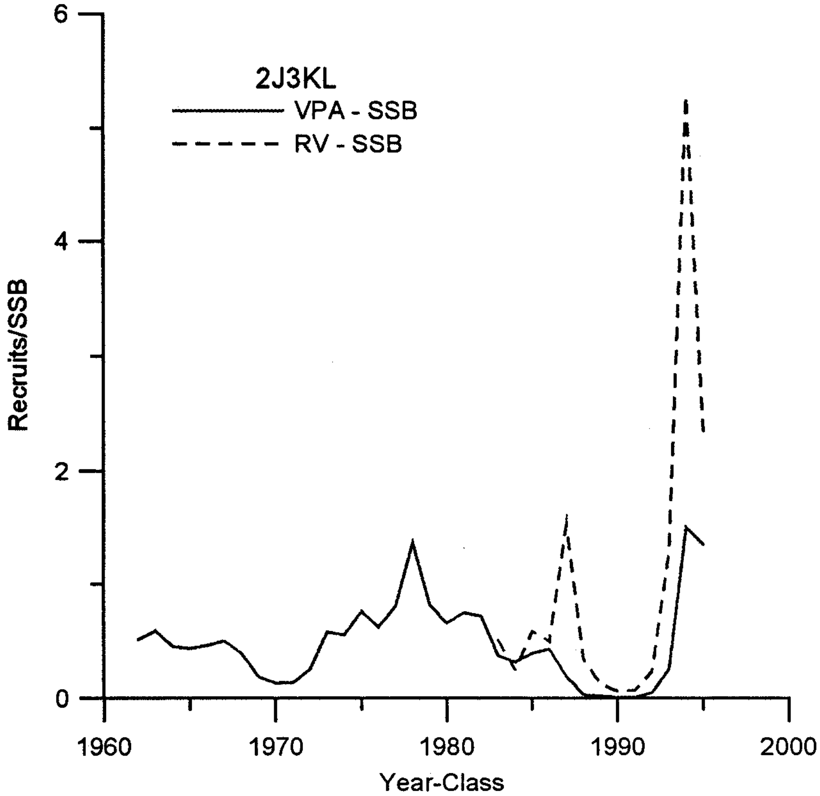
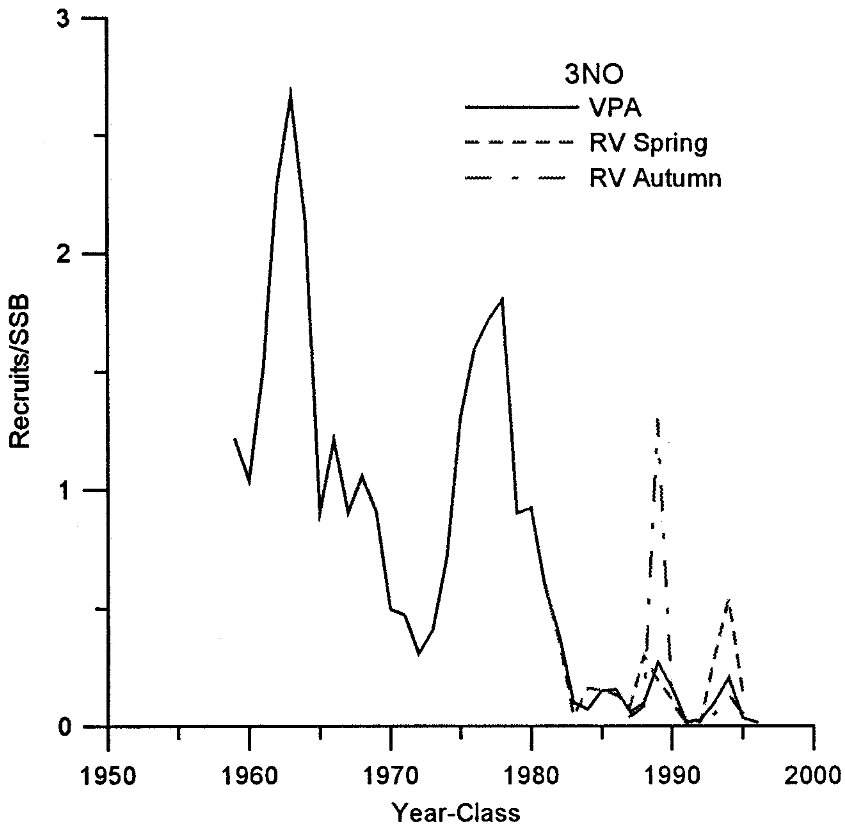


Figure 3. Survival indices, estimated as the number of age three year old cod divided by the spawning stock biomass (SSB) for northern cod (2J3KL), Grand Bank cod (3NO) and St. Pierre Bank cod (3Ps).


2J3KL
VPA - SSB
RV - SSB
Recruits/SSB
Year-Class
0
2
4
6
1960
1970
1980
1990
2000


3NO
VPA
RV Spring
RV Autumn
Recruits/SSB
Year-Class
0
1
2
3
1950
1960
1970
1980
1990
2000

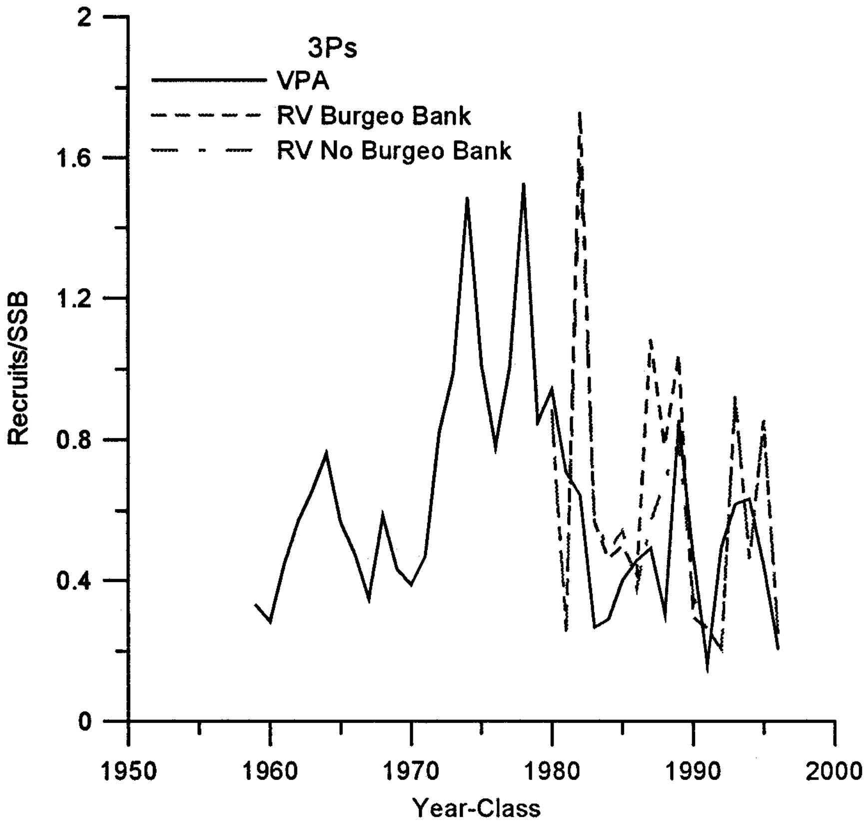
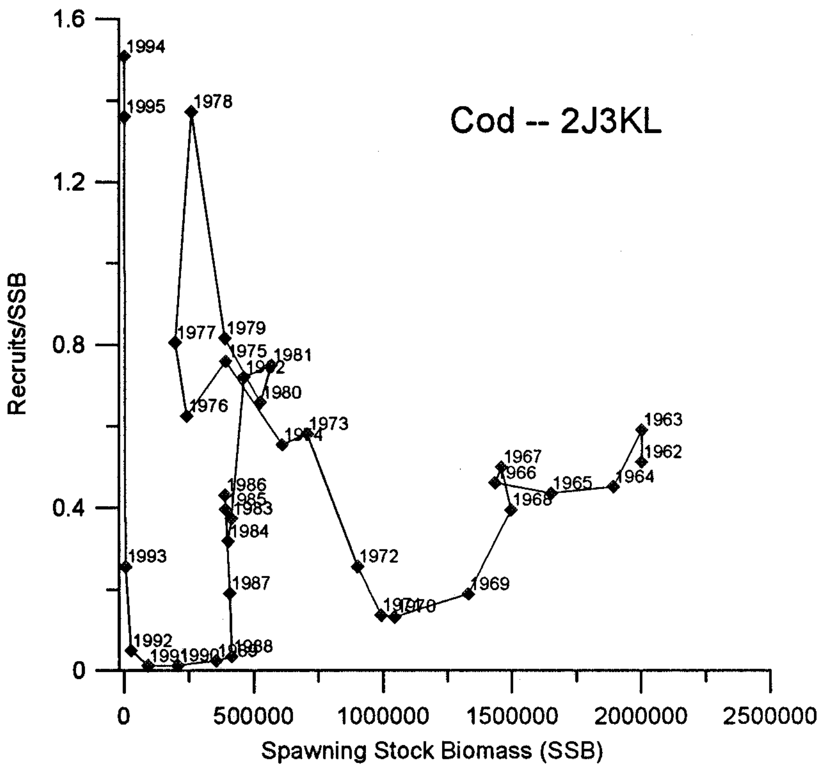
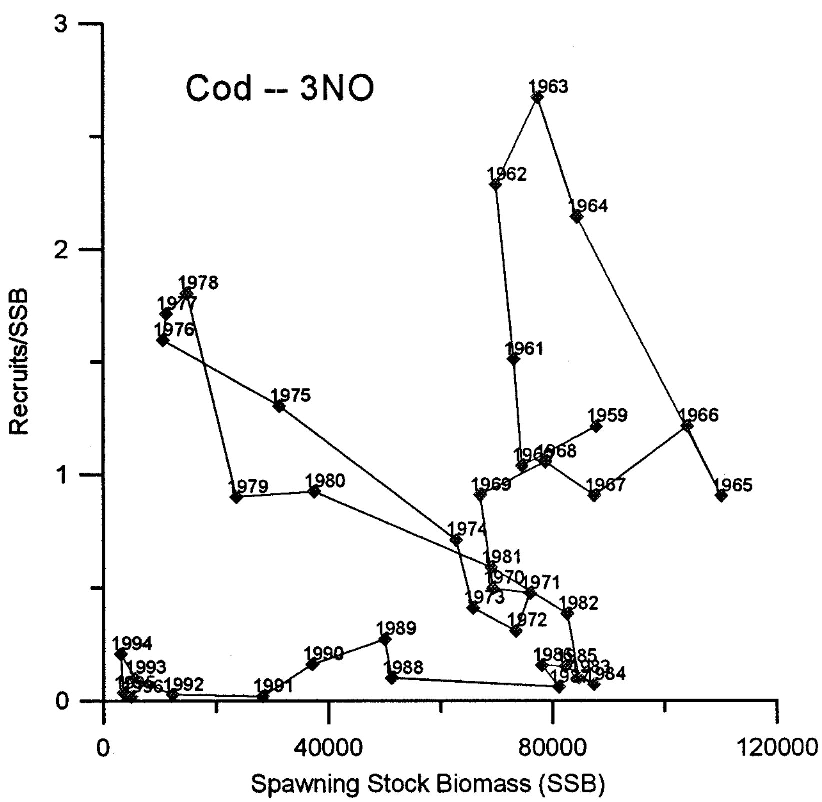


Figure 4. Comparison of survival indices, estimated as the number of age three year old cod divided by the spawning stock biomass (SSB) from Sequential Population Analyses (VPA) and as the mean number per tow of age three cod divided by SSB estimated from bottom trawl surveys (RV). For northern cod (2J3KL) surveys were available for autumn. For Grand Bank cod (3NO) spring and fall surveys are available for some years. For St. Pierre Bank cod (3Ps) estimates are presented for different spring survey areas that include and exclude Burgeo Bank from the estimates.


Cod -- 2J3KL
Recruits/SSB
Spawning Stock Biomass (SSB)
0
0.4
0.8
1.2
1.6
0
500000
1000000
1500000
2000000
2500000


Cod -- 3NO
Recruits/SSB
Spawning Stock Biomass (SSB)
0
1
2
3
0
40000
80000
120000

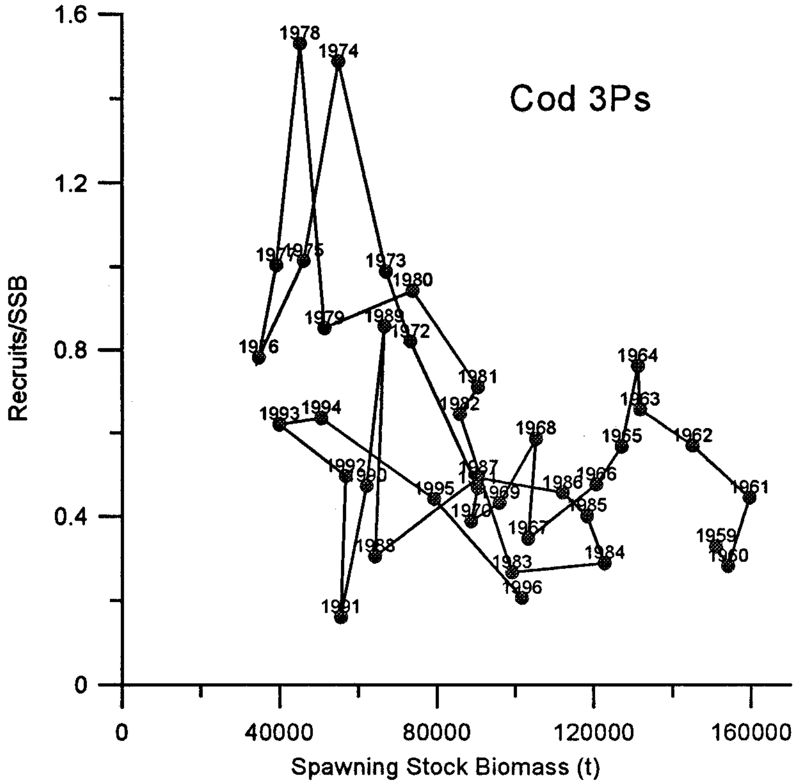


Figure 5. Survival indices, estimated as the abundance of three year old cod divided by the spawning stock biomass (SSB), compared to SSB for northern cod (2J3KL), Grand Bank cod (3NO) and St. Pierre Bank cod (3Ps).

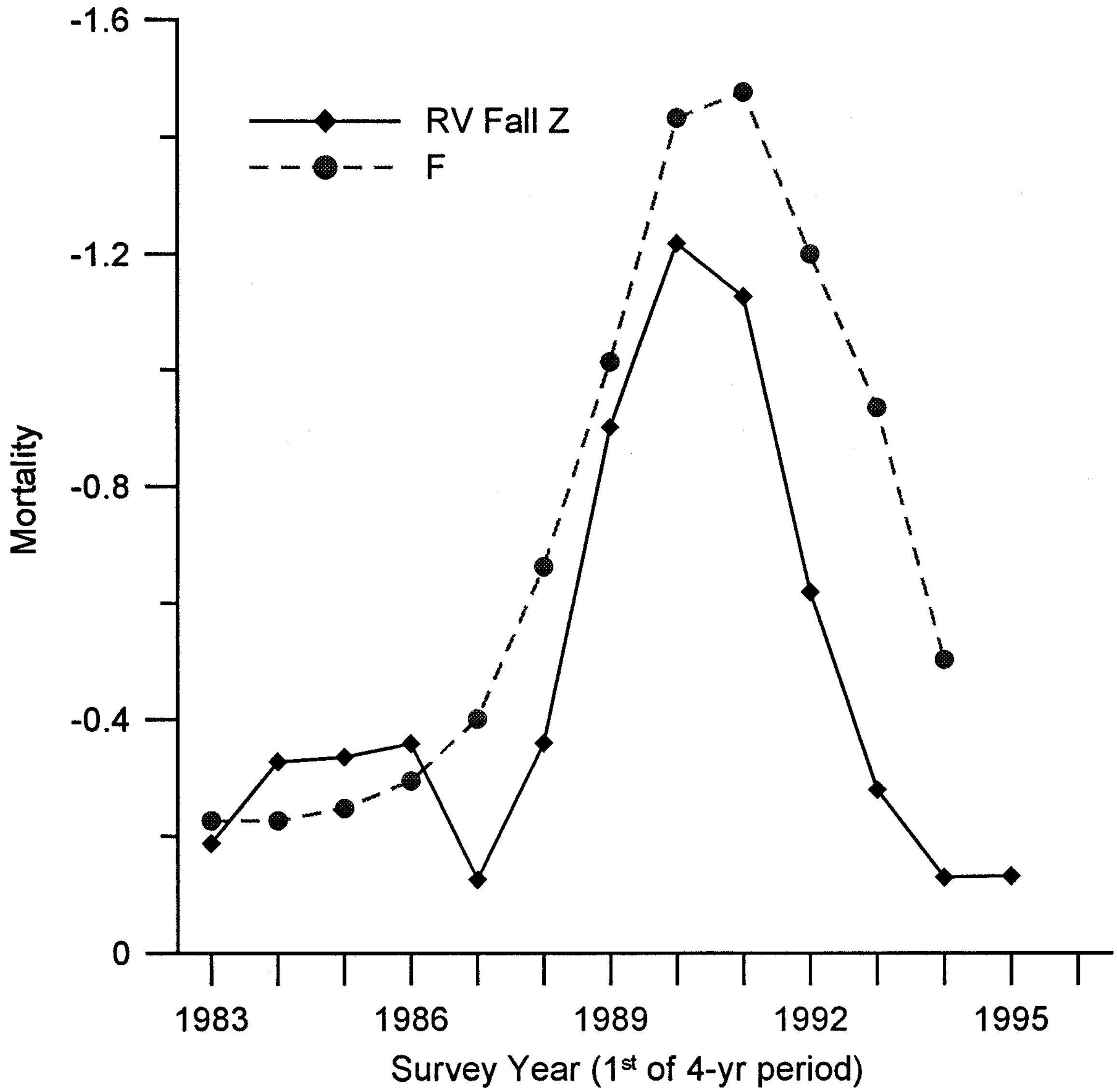


Figure 6. Instantaneous mortality estimated from research vessel surveys for the northern cod stock (2J3KL) for ages 3-7 years for four year time periods, beginning with the 1983-1986 period.

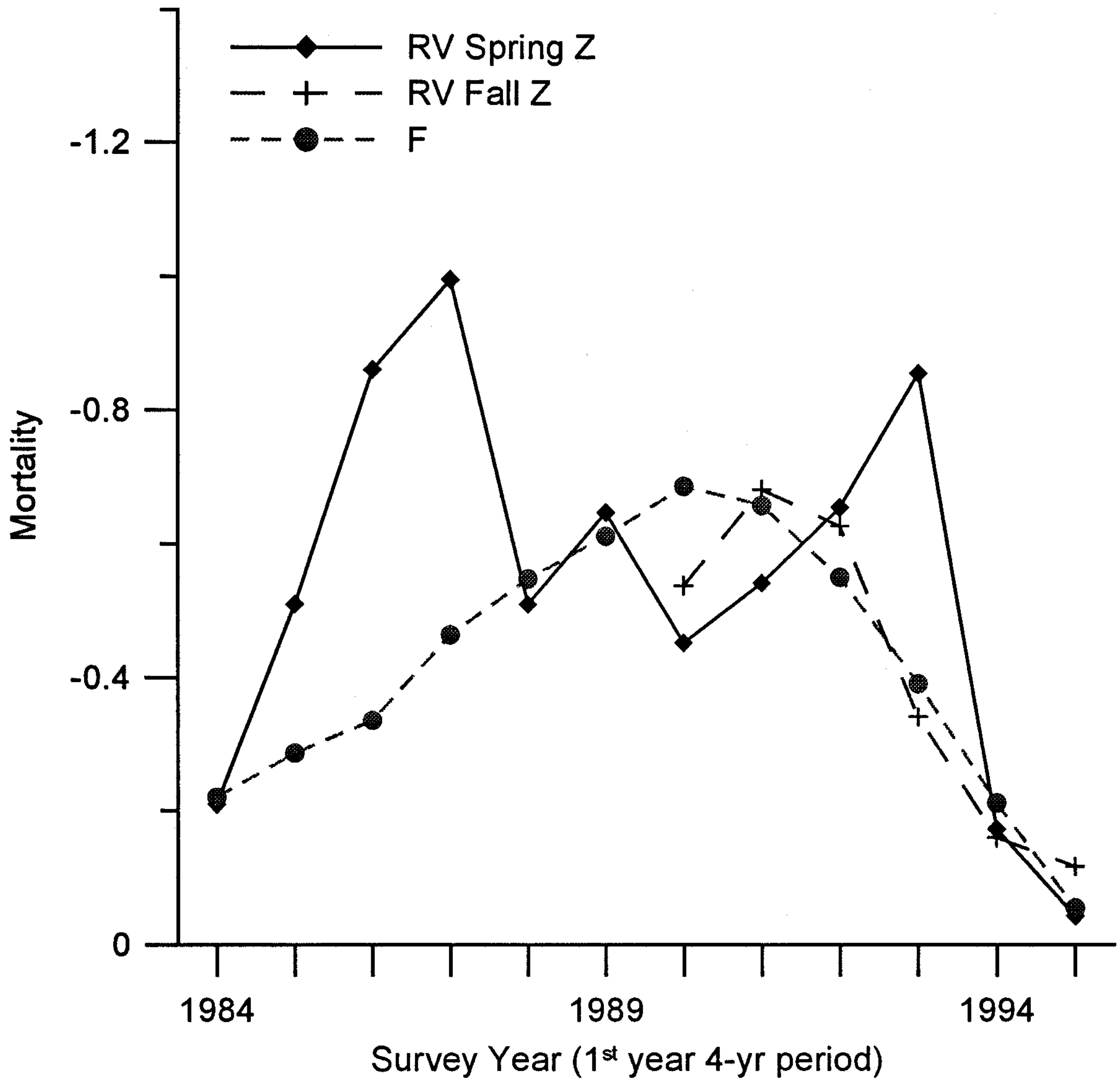


Figure 7. Instantaneous mortality estimated from research vessel surveys for the Grand Bank cod stock (3NO) for ages 3-7 years for four year time periods, beginning with the 1984-1987 period.

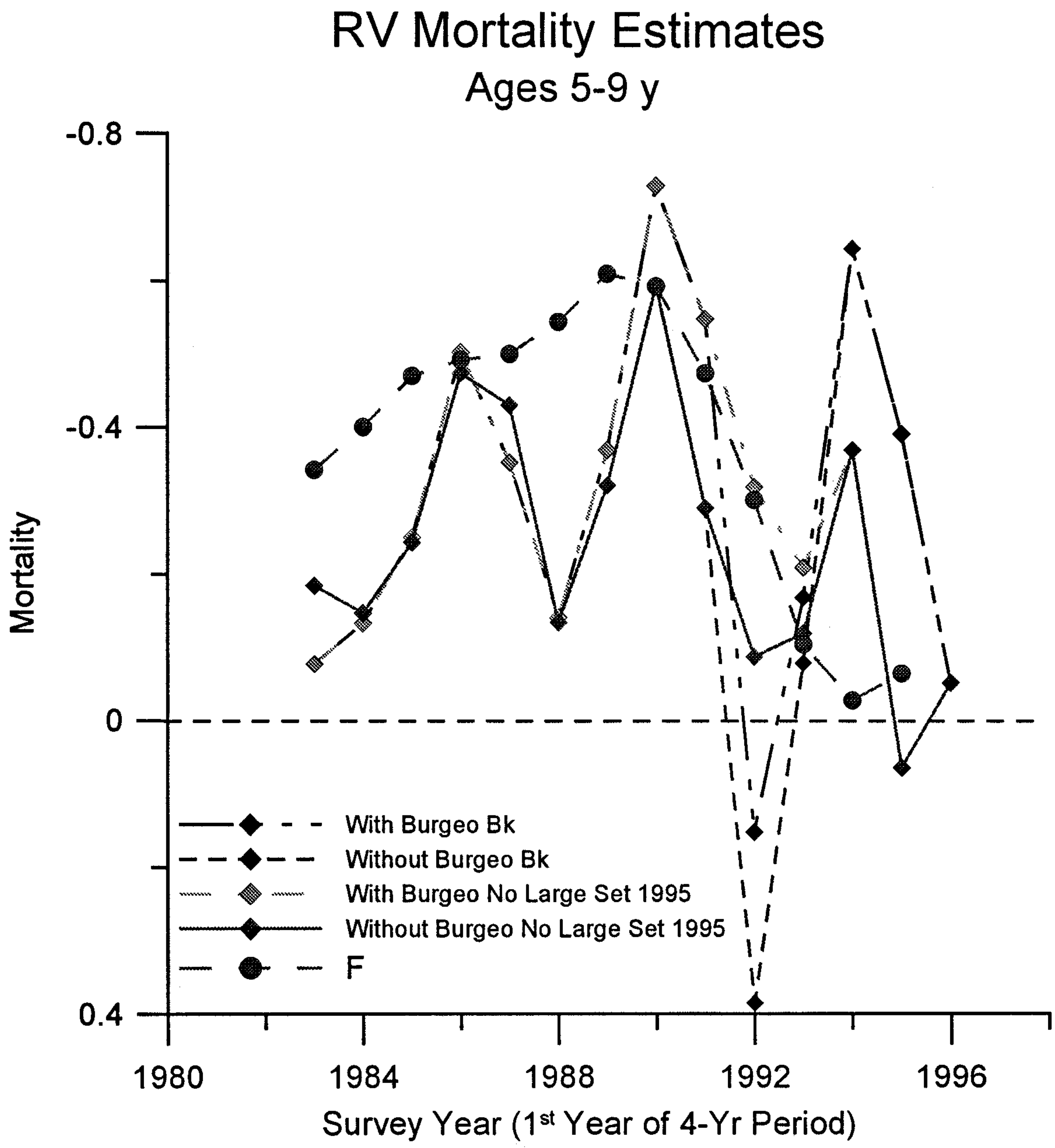


Figure 8. Instantaneous mortality estimated from research vessel surveys for the St. Pierre Bank cod stock (3Ps) for ages 5-9 years for four year time periods, beginning with the 1983-1986 period.

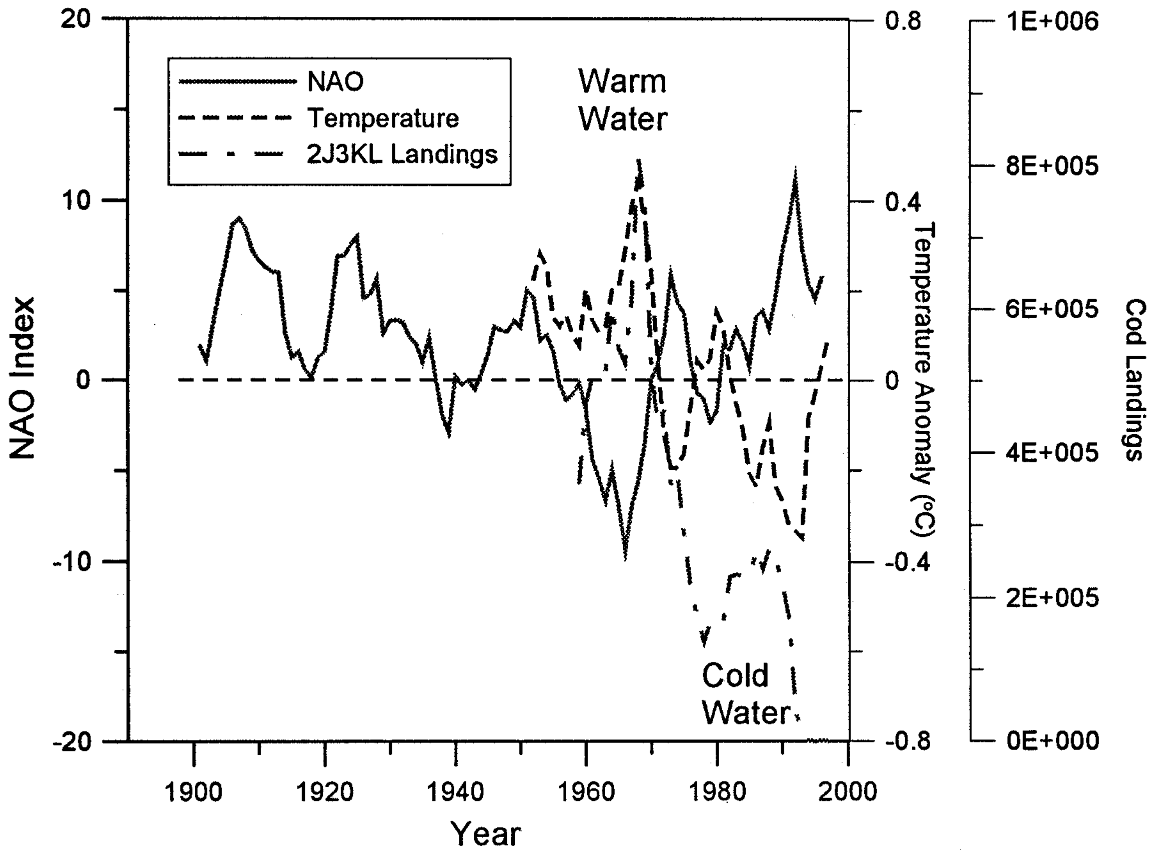


Figure 9. North Atlantic Oscillation (NAO) index, water temperature off Newfoundland (0-180 m) and cod landings from the Northern cod stock (2J3JK). The NAO and temperature data have been filtered using a seven year running average.

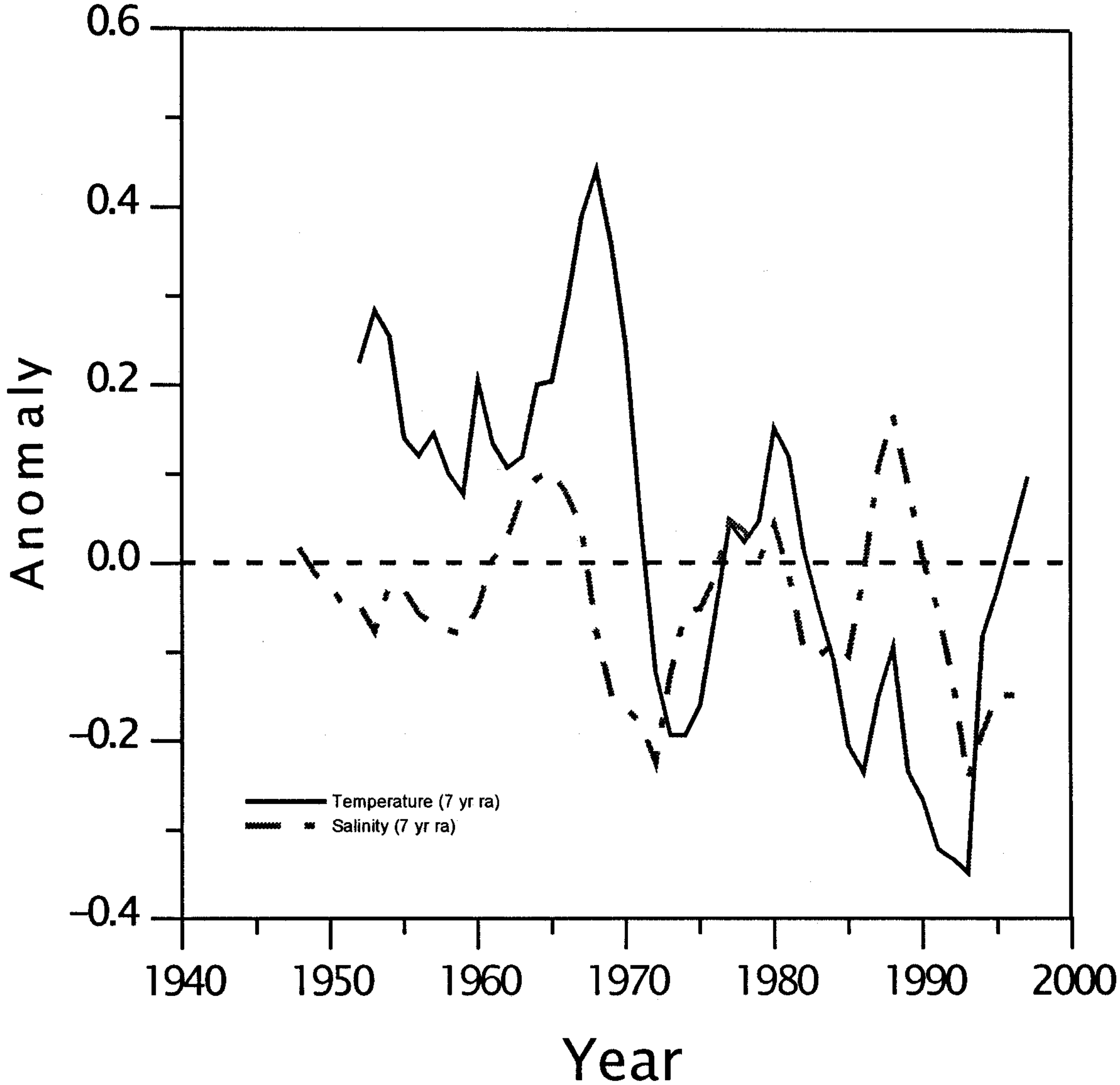


Figure 10. Annual temperature and salinity anomalies measured off Newfoundland for the upper water column (0-180 m). The data have been filtered using a seven year running average.

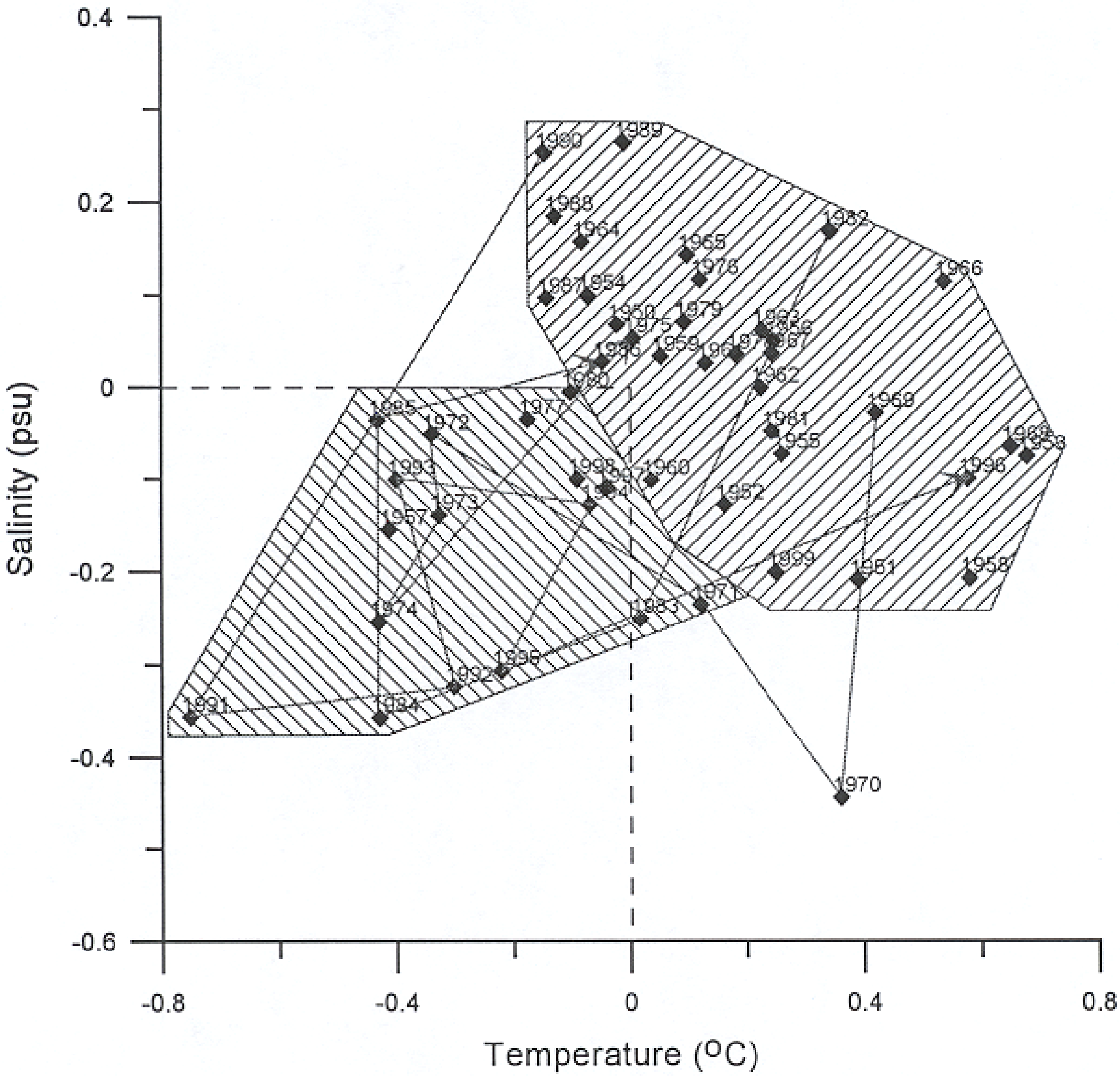


Figure 11. Annual temperature and salinity anomalies measured off Newfoundland for the period 1950-1999. The two polygons represent periods of high temperatures and both high and low salinities compared to periods of low temperature and low salinity. The arrows connect three time series of temperature-salinity values when conditions changed abruptly from the high to low polygon areas.

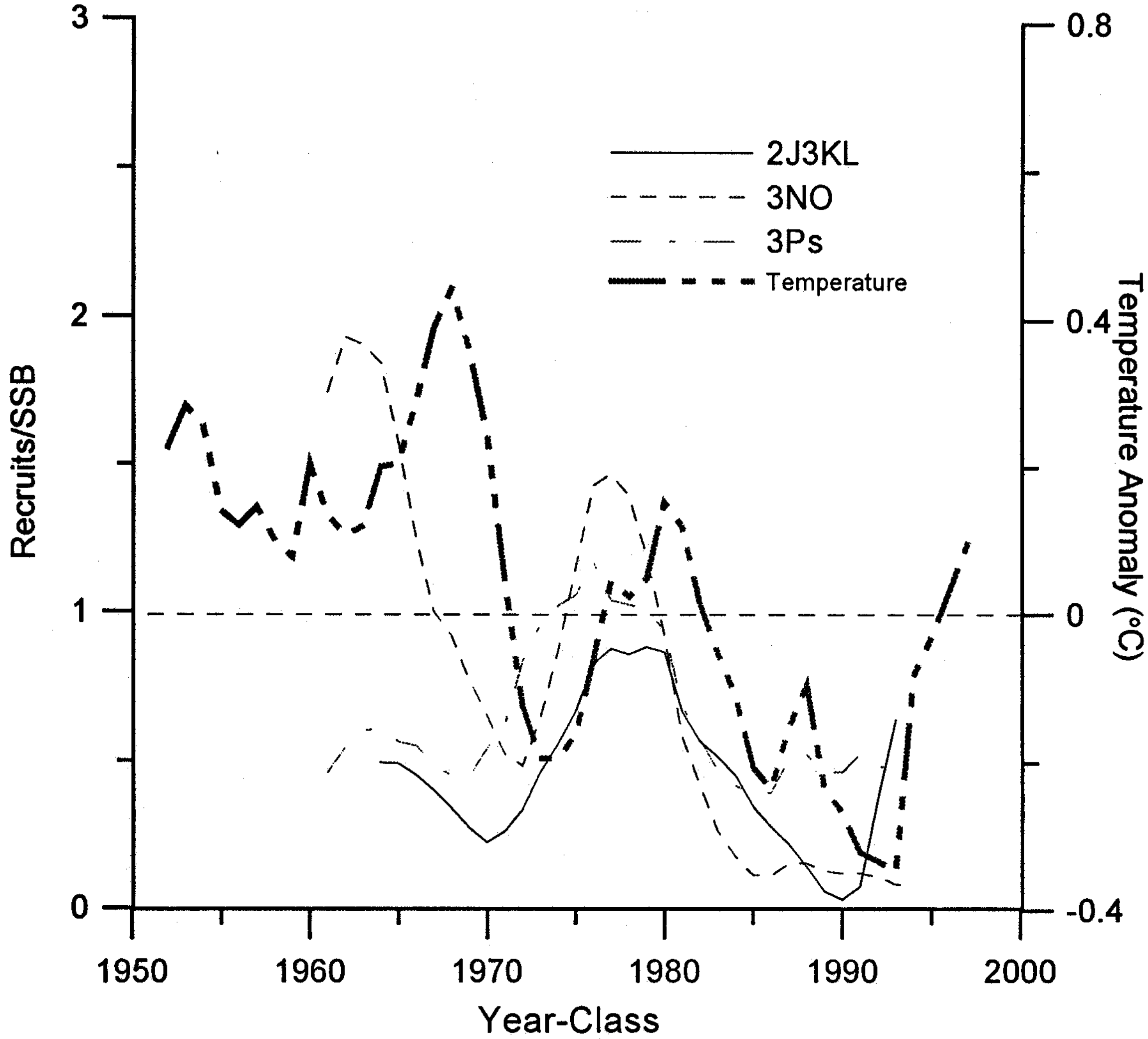


Figure 12. Time series of cod survival indices and ocean temperature in the Newfoundland region. The data have been filtered using a five year running average.