International Council for the Exploration of the Sea **CM 2002/W:10**

The current status of operational oceanography and its integration in fishery resource stock assessments in the Newfoundland Region of Atlantic Canada

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Abstract

Environmental observations and ocean climate variability indices are routinely collected and complied by fisheries laboratories in many ICES member countries throughout the North Atlantic. Variations in the physical oceanographic environment are thought to influence the abundance (recruitment, survival), and behavior (distribution, catchability) of many marine organisms and hence the management and operations of the fishing industry. Therefore, the integration of environmental information into fishery resource stock assessments for management requirements in a quantitative manner is a pressing issue and one that is receiving increasing attention. A review of preliminary efforts in the Newfoundland Region of Atlantic Canada to incorporate environmental information into fish and invertebrate stock assessments is presented. In general, variations in the oceanographic environment appear to be associated with trends in production in several marine species inferred from commercial fisheries (CPUE) and assessment surveys. Results indicate that environmental factors may be important at early life history stages, particularly for crustacean populations. Statistical models were employed to explore relationships between invertebrate production and changes in the oceanographic environment in Newfoundland waters. The results indicate that even though the uncertainty in the predictions is generally large, the information can be a valuable addition to a suite of indicators used to assess current status and future prospects for the management of a number of species of marine organisms.

Keywords: ocean climate, temperature, fisheries, invertebrates, stock assessments

Introduction

Oceanographic observations are routinely collected and complied by fisheries laboratories in many ICES member countries in the north Atlantic, either by directed oceanographic surveys or as part of stock assessment surveys. The results from these surveys in the northwest Atlantic indicate that the past several decades have been a period of considerable variability in the marine ecosystem of the Newfoundland Shelf (Colbourne *et al*., 1994; Drinkwater, 1996; Colbourne, 2001, Drinkwater *et al.*, 2001). In particular, the decade of the 1990s has experienced some of the most extreme variations since measurements began during the mid-1940s (Colbourne and Anderson, 2002). These extreme variations, particularly in the thermal habitat of many marine species, are thought to influence the abundance, distribution and catchability of marine organisms and hence the management of the fishing industry (Parsons and Lear, 2001). Therefore the integration of environmental and process information into various stock assessments in a quantitative manner is a pressing issue and one that is receiving increasing attention (ICES, 2002, 2001).

Several working groups are currently addressing this issue, including one under the Canadian Department of Fisheries and Oceans Fisheries Oceanography Committee (FOC). Environmental information is still used only in a qualitative way in the regional assessment process (RAP) in Atlantic Canada, although quantitative applications have been used in forecasting the pre-fishery abundance of Salmon, for example, in the Northwest Atlantic (Reddin and Friedland, 1993). Generally however, the effort to date has been restricted to environmental overviews, which are sometimes aimed at the habitat of the species being assessed. At best, this effort usually results in a brief description of environmental conditions to be included in the stock status reports. However, at recent invertebrate assessments, environmental-stock relationships have been presented and discussed in detail and some preliminary attempts at predictive modelling were attempted. The result of this effort in now one of the indicators that formed the basis of the outlook for the stock and is normally included in a spreadsheet summary of the status of the stock, the so-called ‘traffic-light’ approach.

The first steps towards the integration of environmental information into stock assessments include establishment of associations or correlations between environmental signals and trends in production indices of various fish and invertebrate stocks and exploration of the predictive powers of statistical models using environmental signals. This should eventually lead to the inclusion of both physical and biological information in process-oriented effects, which would account for variations in primary and secondary production in ecosystem models. A review and short description of environmental-stock relationships for some marine species of fish and invertebrates in Newfoundland Shelf waters was recently compiled by Colbourne et al. (2002). A full statistical evaluation including their predictive powers however was not included and it was noted that in many cases the time series are too short to offer the statistical significance necessary for auto-regressive type modelling. In this manuscript we review the environmental-stock associations for three species of invertebrates currently assessed for Newfoundland waters. Statistical models are then used to forecast production in these species by using a commercial fisheries (CPUE or landings) index and the apparent correlation with changes in the oceanographic environment. This effort should be considered a starting point towards the goal of using information from operational oceanographic observing programs in the assessment and management of marine resources.

Oceanographic Monitoring Programs

The monitoring of the physical environment in Atlantic Canada has been a priority for the Canadian Department of Fisheries and Oceans since the early 1950s, when the Fisheries Research Board of Canada implemented it's annual oceanographic monitoring survey for the Newfoundland Shelf. During this survey oceanographic measurements along standard sections and stations (Fig. 1) on the Newfoundland and Labrador Shelf are made during mid-summer, initially under the auspices of the International Commission for Northwest Atlantic Fisheries (ICNAF, 1978) and currently for the Northwest Atlantic Fisheries Organization (NAFO). The 50-year plus time series of ocean climate indices from this survey, such as the volume of the cold intermediate layer (CIL) of sub-polar water on the coastal shelf is often used to gauge ocean climate change and it's influence on many species of marine organisms in Newfoundland waters. Additionally, as part of the expanded and enhanced Canadian Atlantic zonal oceanographic monitoring program (AZMP) some of these sections are now sampled on a seasonal basis and include measurements of biological and chemical oceanographic variables (Therriault *et al.,* 1998). The main objectives of this initiative are to establish the temporal and spatial distribution and abundance of plant pigments, nutrients, microzooplankton and mesozooplankton in relation to the physical environment. This monitoring program should allow an understanding of changes in ecosystem productivity and changes in ecosystem structure over time.

A considerable increase in the monitoring effort in Canadian waters occurred during the 1970s with the startup of the stratified random ground fish trawl surveys on the Newfoundland Shelf in NAFO sub-areas 2 and 3. Each NAFO sub-area was stratified based on the depth contours from available standard navigation charts. Areas within each NAFO division, within a selected depth range, were further divided into strata and the number of fishing stations in each stratum was chosen based on an area weighted proportional allocation (Doubleday, 1981; Bishop, 1994; Murphy, 1996). Surveys have been conducted in both the spring and fall in some divisions initially in water depths from 300-400 m and recently to 1500 m. During all of these surveys oceanographic data were collected at most fishing set locations and archived in oceanographic databases as well as included in the trawl set details. From 1971 to 1988 temperature data on these surveys were collected using bottles at standard depths and/or bathythermographs, mechanical or expendable (MBT/XBT), which were deployed usually at the end of each fishing set. Since 1989 net-mounted conductivity-temperature-depth (Seabird model SBE-19 CTD systems) recorders have replaced XBTs. This system records temperature and salinity data during trawl deployment and recovery and for the duration of the fishing tow. The random stratified fish samples obtained from these surveys together with commercial fisheries data form a basis to determine recruitment and population abundance for demersal fish stock assessments and more recently for the assessment of invertebrates.

In addition, under the Northern Cod Science Program (NCSP) of the early-1990s several new initiatives were undertaken to increase the understanding of ecosystem processes on the Newfoundland Shelf. One of these included a comprehensive large-scale survey of the marine pelagic environment on the Newfoundland and Labrador Shelf that was conducted for the years 1994-1999 (Anderson and Dalley, 1997; Dalley *et al.,* 1999, 2000). These surveys, initiated after the collapse of the cod stocks of Newfoundland, were designed to measure pre-recruit pelagic (0-group) cod as well as providing a full multi-species measure of plankton and nekton for the study area, together with a comprehensive temperature and salinity survey.

Collectively, these surveys, plus observations from fishing vessels and ships of opportunity, provided a comprehensive oceanographic data set for the Newfoundland Shelf region with good temporal and spatial coverage for most of the decades since the 1950s. All of the hydrographic data are quality controlled and archived in Canada's national Marine Environmental Data Service (MEDS) database in Ottawa. Working copies are maintained in zonal databases in Fisheries Laboratories throughout Atlantic Canada.

Results

Many physical and biological interactions in the marine ecosystem are probably non-linear and operate through complex mechanisms throughout the ecosystem over a broad range of time and space scales. These interactions are further complicated by variations in fishing mortality. Therefore, simple correlations between individual environmental indices with measures of marine production often break down as different physical or biological factors begin to dominate various levels of the ecosystem and life stages of marine organisms. However, trends which coincide in the physical and biological environment may reflect significant change related to production in marine ecosystems over the long term. In this section we present environmental-stock relationships for three species of invertebrates that are assessed in Newfoundland waters, namely, snow crab *(Chionoecetes opilio)*, northern shrimp *(Pandalus borealis)* and American lobster (*Homarus americanus*).

The commercial fisheries catch-per-unit-effort (CPUE) time series for snow crab and shrimp in this study are considered as a proxy for production estimates in the absence of any other biological measure. However, landings data are considered a more reliable index of abundance for American lobster in this region. For the species considered here, the long-term trends in the CPUE/landings coincide with trends in the physical oceanographic environment at time lags corresponding to the difference between the approximate age of recruitment to the fishery and the egg and larval stages of each organism. On an annual basis however, these correlations often break down or are not statistically significant. Nevertheless, the results indicate that environmental factors may be important at early life history stages for northern shrimp, snow crab, lobster and other species in Newfoundland waters. Using this information, an autoregressive, integrated moving average (ARIMA) Box-Jenkins (1976) type procedure was used to explore a predictive model between production in the three species of crustaceans and changes in the oceanographic environment. Many of the details of this modelling effort are found in Parsons and Colbourne (2000). Taking advantage of the apparent correlation between the commercial catch information and the environment at time lags corresponding to the early life stages of each species, some forecasting potential using transfer functions is realized. Projections of the CPUE/landings can therefore be developed by including past values of environmental data in addition to using the auto-correlation within the stock response time series. However the uncertainty in the predictions is generally large and increases with time.

Snow Crab (Chionoecetes opilio)

Recruitment in many commercially important crab stocks in the Bering Sea and Gulf of Alaska appears to be related to decadal shifts in ocean climate (Zheng and Kruse, 2000). Strong year classes in king and tanner crab stocks in this area were significantly associated with strong cyclonic winter circulation, as indexed by the Aleutian Low and low sea-surface temperatures. Year class strength of Eastern Bearing Sea snow crab was noted to be quite different from that of other crab stocks, but appeared to be negatively, although not significantly, associated with surface temperature.

Snow crab fisheries in Newfoundland and Labrador (Dawe and Colbourne 2002) began in 1968 and a 29-year time series of commercial catch-per-unit-effort (CPUE) data (1973-2001) is available for the eastern Newfoundland shelf, including the northern Grand Bank (NAFO Div. 3L). CPUE is expressed as kg per trap haul, and is unstandardized. Although this series does not account for annual variation in fishing practices (e.g. soak time), it is believed to generally reflect long-term trends in the abundance of the resource. CPUE was found to be negatively correlated with a local bottom temperatures and positively correlated with indices of the areal extent of cold water (Cold Intermediate Layer, CIL) on the Grand Banks. The association was strongest when each environmental index was lagged by 8 years, the approximate age of snow crab recruitment (Fig. 2). This suggests that cold conditions early in the life cycle (e.g. pelagic larval stage or settling megalopal stage) are somehow favorable for production or early survival. Recent high CPUE values are associated with a cold oceanographic regime that extended to 1993.

Time series analysis was carried out using CPUE as the response variable and a vertically integrated Jan-June Station 27 temperature index as an input variable. An auto-regressive parameter was the most significant determinant of CPUE, reflecting strong auto-correlation in the CPUE series due to periodicity in crab recruitment. However the temperature index with an 8-year delay or lag was a significant parameter in the model. In general the model was able to reproduce the observed CPUE reasonably well. The model projections indicate the CPUE may begin to decline in the near future, due to warm conditions since 1995, but forecasts are associated with very broad confidence intervals, which tends to increase with increasing time (Fig. 3).

Northern Shrimp (Pandalus borealis)

The importance of environmental influences affecting the dynamics of Pandalid shrimp has been recognized for many years (Rasmussen, 1953; Parsons and Colbourne, 2000; NAFO, 2000). A commercial fishery for northern shrimp on the mid-Labrador Shelf within NAFO Div. 2HJ has been conducted since the mid-1970s. Catch and effort data from the commercial vessel logbooks were compiled for all years from 1977-1998 within this area. The catch-per-unit-effort (CPUE) was then estimated as kg per hour. The annual CPUE was then standardized by multiple regression to account for variations in the fishing vessel, area fished and the time of the fishery (Parsons *et al.,* 1999). This standardized annual series has been used as a measure of fishery performance and as an indicator of the fishable stock biomass.

In a recent study by Parsons and Colbourne (2000) a number of environmental variables were found to be associated with the shrimp CPUE, including Station 27 bottom temperatures, CIL, sea-ice cover and the NAO (Fig. 4). The strongest correlations (after prewhitening to account for autocorrelation) of -0.42 and 0.39 were found with sea-ice cover at lags of 0 and 6 years respectively. The negative correlation at no lag simply indicates the adverse affect of heavy ice conditions on fishing activity and the 6-year lag (the mean age of the commercial catches) correlation implying that cold years contribute positively to the survival of larvae and juveniles in the same year. The time series displayed in Fig. 4 show a declining CPUE during the late-1970s and early-1980s, reaching a minimum by the mid-1980s corresponding to the minimum in the 6-year lagged sea-ice cover and low NAO values. During the mid- to late-1980s the CPUE increased marginally and by the latter half of the 1990s it increased significantly corresponding to the increase in the lagged sea ice and NAO climate indices.

Time series analysis was carried out using CPUE as the response variable and the environmental variable (sea-ice cover) an input variable in the same way as was done for snow crab. Again the auto-regressive parameter was the most significant determinant of CPUE, reflecting the strong auto-correlation in the CPUE series of northern shrimp. Sea-ice cover with a lag of 6-years was the most highly correlated environmental variable. In general the model was able to reproduce the observed CPUE reasonably well. The model projections based on the 6-year lagged correlation with the environmental index indicate that the CPUE may begin to decline in the near future, again due to warm conditions during the latter part of the 1990s. Again the forecasted values of the CPUE are associated with very broad confidence intervals increasing with time, indicating that projected CPUE could remain stable or at worst experience a 50% decline over the next few years (Fig. 5).

***Lobster* (*Homarus americanus*)**

Newfoundland lobster landings have been reported in the official fisheries statistical system by statistical areas since 1953. Statistical areas generally coincide with the larger bays around the island and in later years these became designated as Lobster Fishing Areas, without boundary change for the most part, for fishery management purposes. Landings for Notre Dame Bay (Statistical Area B, LFA 4) from 1953 to 1999 together with Station 27 upper layer (50 m) July-August average temperature are shown in Fig 6. The temperature time series shows the highest correlation with the lobster landings at a 9-year lag, with higher landings associated with higher temperatures. The 9-year lag in the temperature-landings correlation corresponds to the estimated time to recruitment for Newfoundland lobsters of 8-10 years (Ennis, 1980). This suggests that warmer water conditions early in the life cycle are somehow favorable for production or early survival for lobster within the inshore environment.

Time series analysis was applied to the lobster landings in a similar manner as for snow crab and shrimp. In this case the landings data were used as the response variable and the inshore summer temperature index with a 9-year lag as an input variable. Again the model was able to reproduce the observed landings reasonably well. The model projections indicate landings may begin to increase slightly in the near future, due to warm conditions since the mid-1990s, but again the forecasts are associated with very broad confidence intervals (Fig. 7).

Discussion and Summary

The results presented indicate that variations in the physical environment may be an important factor in determining the early life survival rates of commercially exploited invertebrates in Newfoundland waters. In particular the extremely cold ocean temperatures in waters of the Newfoundland Shelf during the late 1980s and early 1990s coincided with the survival of large year-classes of snow crab and northern shrimp. Taking advantage of the time lag between the environment and abundance of these species, projections of the level of the resource several years ahead is possible, however, the uncertainty in the predictions is generally large. The results of studies in the waters of West Greenland also indicate that the increase in abundance of northern shrimp coincided with a cooling ocean environment (Buch et al. 2002, Shumway et al. 1985). It is also noted however, that in both regions the increase in invertebrates also coincided with the release of predation pressure due to declining cod stocks (Lilly et al. 2000) and other finfish predators of shrimp, which no doubt plays an important role.

The abundance and recruitment of a broad range of other species of marine and anadromous fish and invertebrates in Newfoundland waters also exhibit clear associations with environmental signals. Some of these include short finned squid (*Illex illecebrosus*) (Dawe *et al.,* 2000), Atlantic cod *(Gadus morhua)* (Colbourne and Murphy 2000, 2002), yellowtail flounder *(Limanda ferruginea)* (Colbourne and Bowering 2001) and Atlantic salmon *(Salmo salar)* (Colbourne et al. 2002) and many species of pelagic o-group organisms (Colbourne and Anderson 2002). Recruitment for the Grand Bank cod stock, for example, experienced a long-term decline during the 1970s until the middle to late-1980s from the highs of the early- to mid-1960s. By the early-1990s recruitment in this stock was in a steep decline and throughout the 1990s it remained at historically low levels (Stansbury et al. 1999). Coincident with the changes in cod recruitment on the Grand Bank, ocean temperatures and water salinity in this area during the past several decades have experienced near-decadal oscillations superimposed on a general downward trend (Fig. 8 top panel). Recruitment was also associated with the long-term trends in the NAO, with low recruitment generally associated with a cold environment (high positive NAO anomaly) (Fig. 8 bottom panel).

The pelagic ecosystem responded in several ways to the changing physical environment on the Newfoundland Shelf during the 1990s. For example the abundance of individual species of o-group pelagic fish including Atlantic cod, sandlance (*Ammodytes* sp.), redfish (*Sebastes* sp.) and American plaice (*Hippoglossoides platessoides*) remained low during the cold early 1990s but increased dramaticlly during the warmer years of the late 1990s. In contrast, the abundance of o-group Arctic cod (*Boreogadus saida*) decreased from 1994 to 1999, and this decrease was associated with the increasing ocean temperatures in the region. The replacement of Arctic species by boreal and temperate species such as capelin and sandlance during the warm years of the late-1990s appear to be a direct response to warm water conditions following the cold period of the early-1990s. This is consistent with the expected biological response of the ecosystem to a warming ocean environment and it's effects on early life stages of pelagic organisms (Anderson *et al.,* 1999, Dalley *et al.,* 2000, Colbourne and Anderson, 2002).

The results presented here and in other studies indicate clear associations between fish and invertebrate survival and production with physical environmental signals across a broad range of species. The results support the generally accepted hypothesis that variations in ocean climate impacts marine production in many species to some extent, particularly in regions near the limits of their distributions. However, while simple physical indices of ocean climate variations such as water temperature, no doubt play a critical role in defining the marine habitat of various species and determining survival of eggs and larvae, recruitment most likely depends on many other complex physical and biological processes, including fishing mortality. Thus the need to move towards an ecosystem approach and process orientated effects at the lower trophic levels is essential if further progress in this area is to be realized.

In conclusion the present analysis was intended to provide a starting point and to investigate associations and correlations between the environment and indices of marine production and to evaluate the potential of statistical modelling in this context. Once clear significant associations or correlations are made between the environment and various measures of marine production, it may then be possible to focus the research necessary to understand the cause and effect mechanisms whereby environmental effects are clearly understood and accounted for in any assessment. It is also clear from this effort that statistical modelling of relatively short time series is of limited value in predicting future abundance of these resources with the confidence required for management purposes. Nevertheless, the information obtained can be a valuable addition to a suite of indicators used to assess current status and future prospects for many species of marine organisms.

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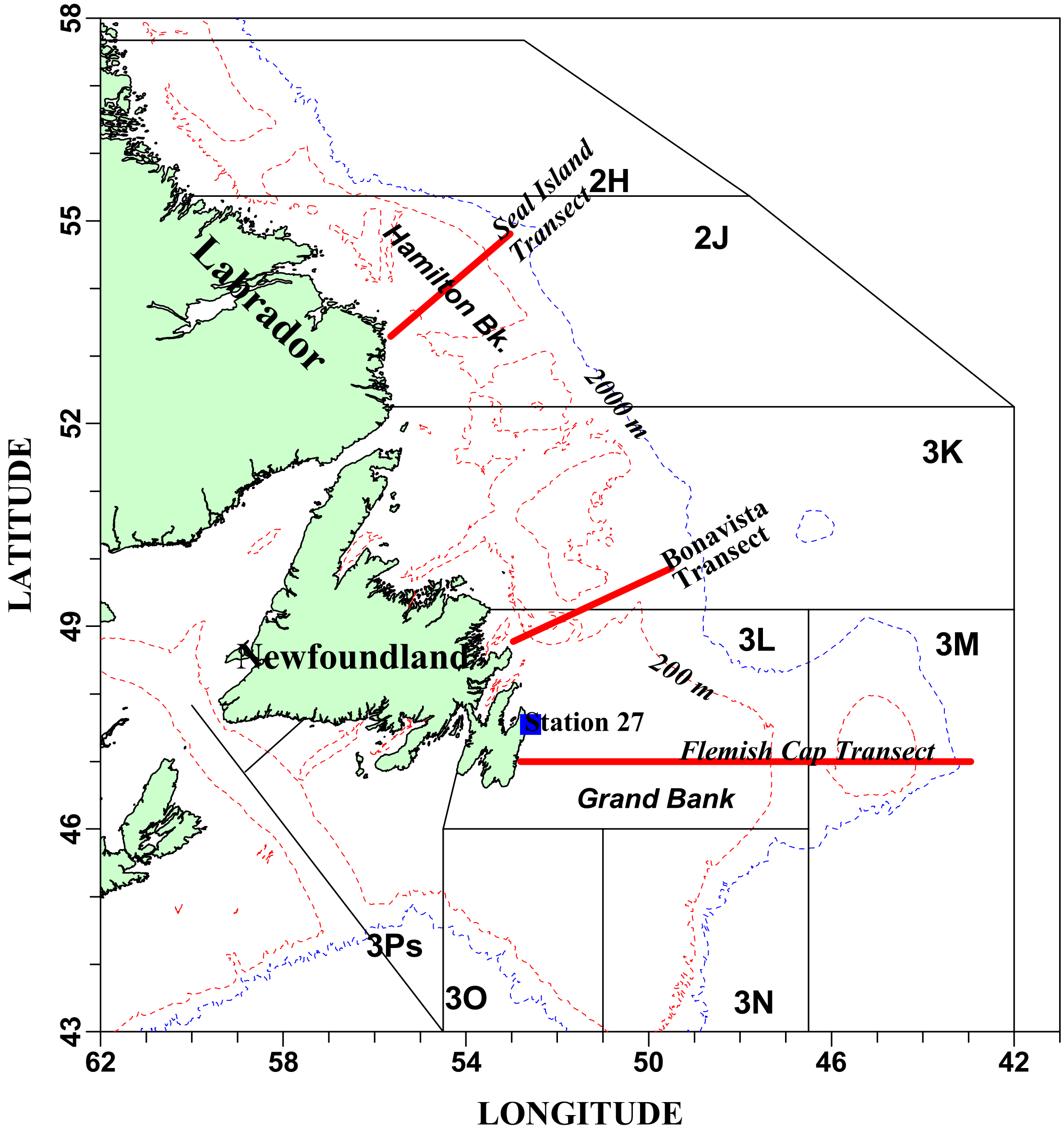

Fig. 1. Regional map showing the positions of standard monitoring sections, Station 27 and the statistical fish management areas established by the Northwest Atlantic Fisheries Organization (NAFO) in the Newfoundland Region.

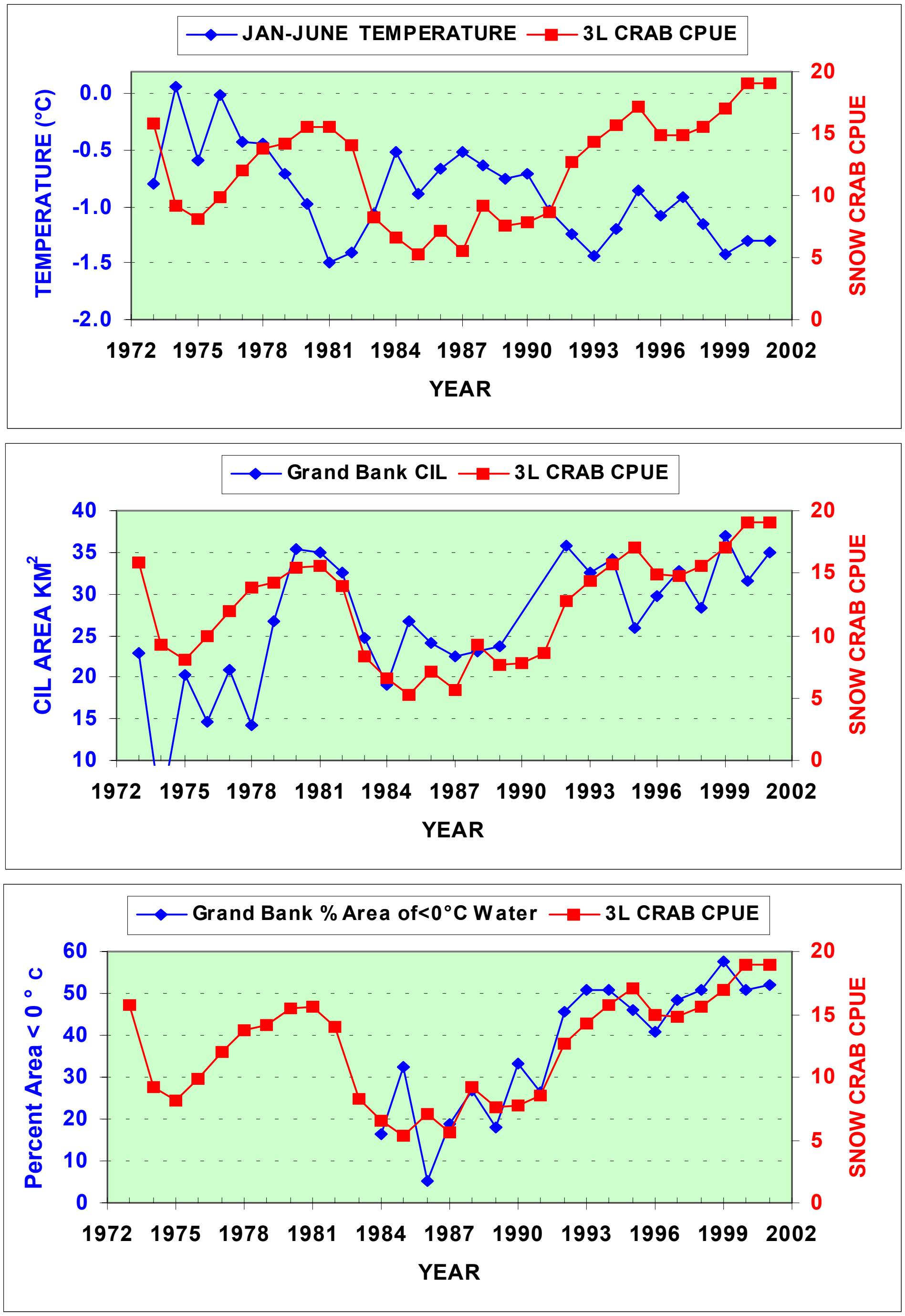

Fig. 2. Annual CPUE of snow crab in NAFO Div. 3L and the time series of Station 27 temperature, Grand Bank CIL area and the % area of the bottom covered by <0°C water on the Grand Bank all lagged by 8-years with respect to the CPUE series.

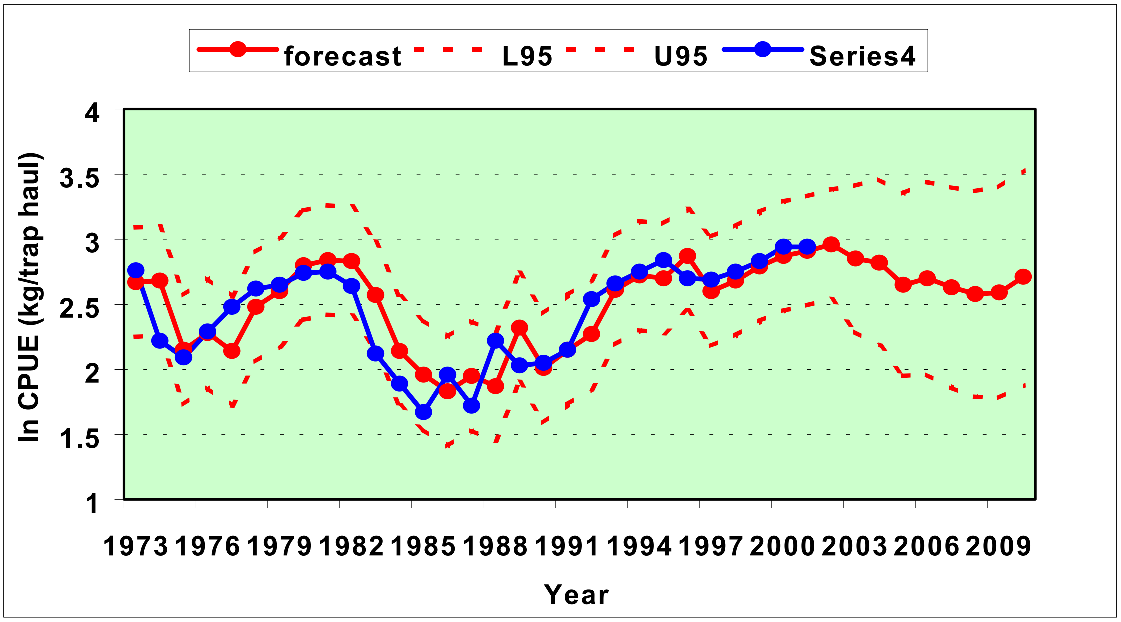

Fig. 3. Annual and predicted CPUE for Grand Bank snow crab in NAFO Div. 3L. The dashed lines are the 95% confidence intervals.

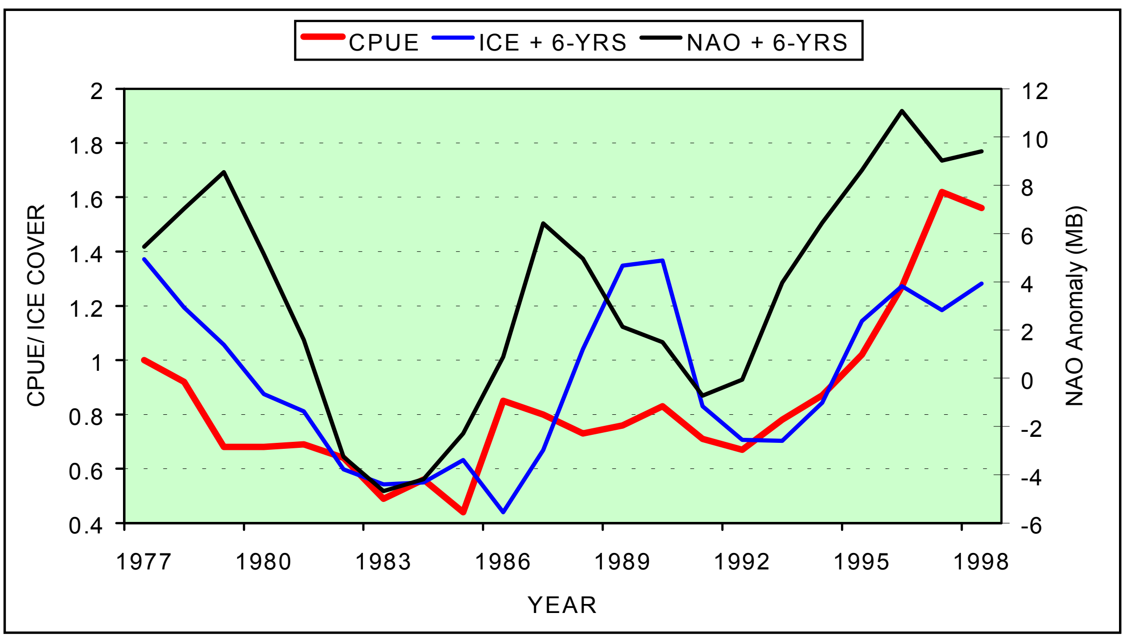

Fig. 4. Annual CPUE of northern shrimp in NAFO Div. 2HJ and the time series of the areal extent of sea ice on the Newfoundland and Labrador Shelf and the NAO index at 6-year lag with respect to the CPUE.

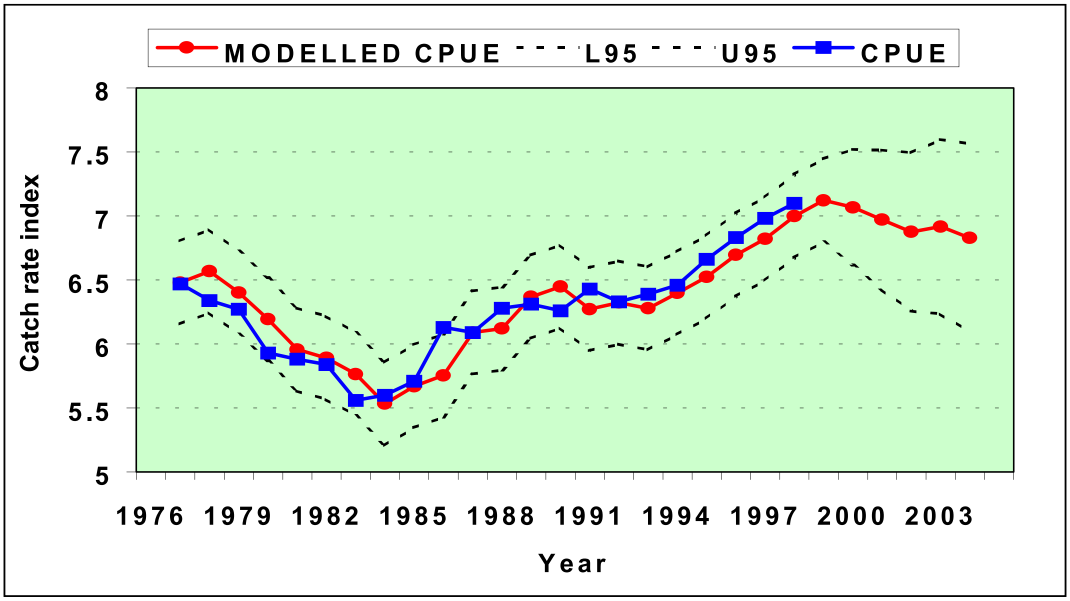

Fig. 5. Annual and predicted CPUE for northern shrimp on the Labrador Shelf in NAFO Div. 2HJ. The dashed lines are the 95% confidence intervals.

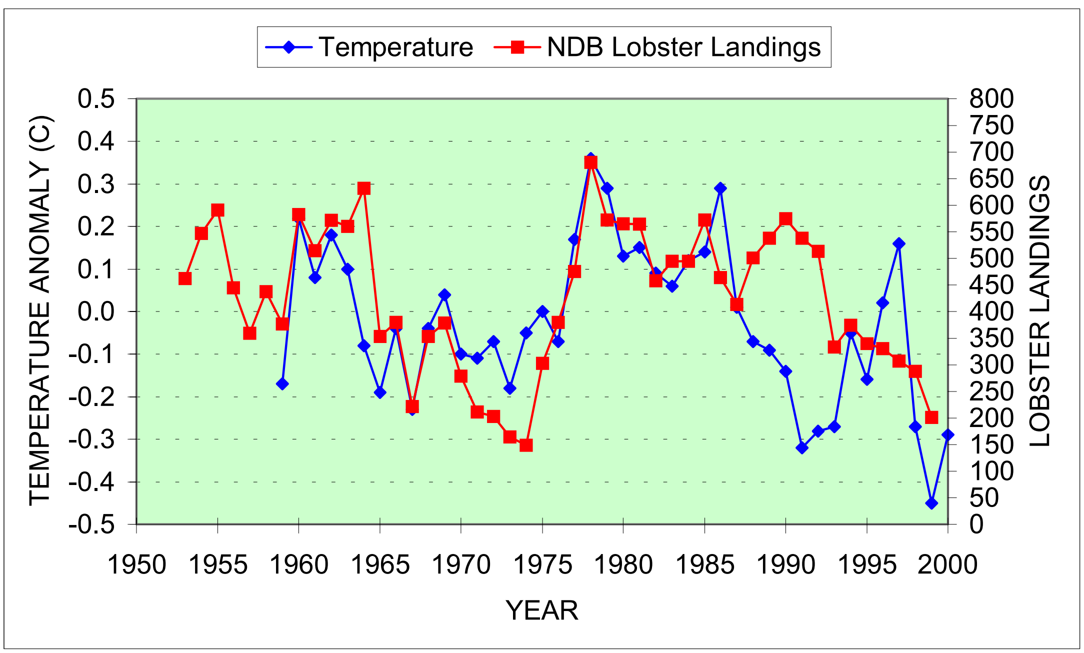

Fig. 6. Annual lobster landings on the northeast Newfoundland Coast NAFO Div. 3K and the time series of Station 27 50-m depth temperature annual at 9-year lag with respect to the landings data.

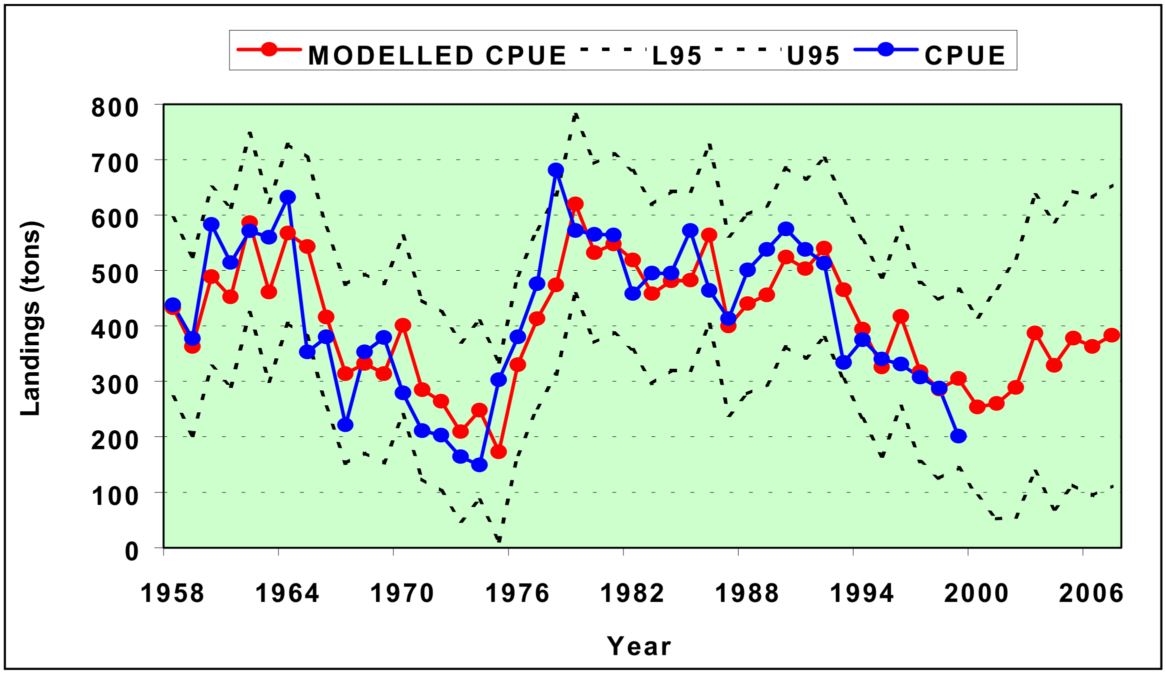

Fig. 7. Annual and predicted lobster landings on the northeast Newfoundland Coast in NAFO Div. 3K. The dashed lines are the 95% confidence intervals.

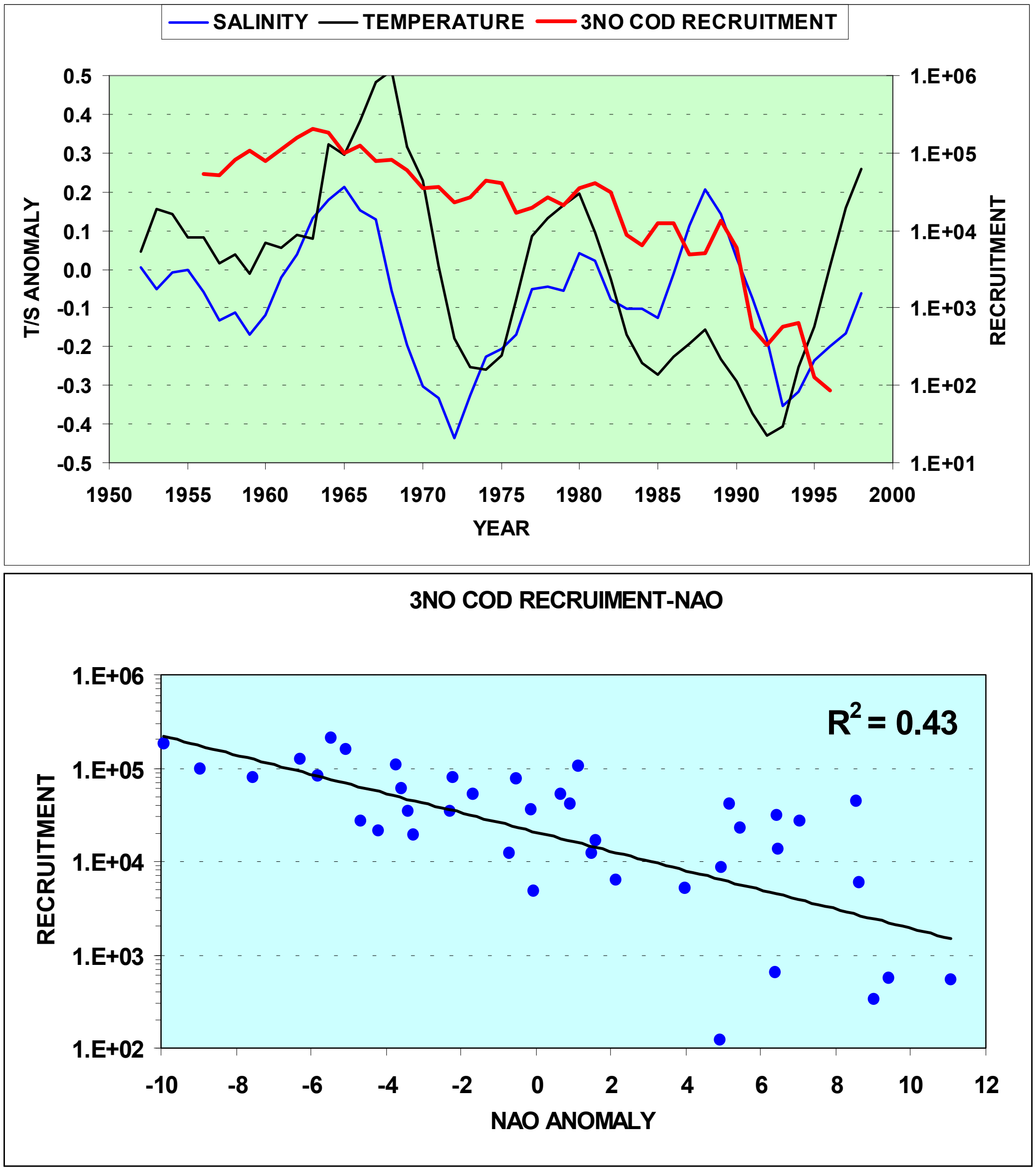

Fig. 8. Recruitment in Grand Bank (Div. 3NO) cod from Sequential Population Analysis (defined as abundance estimated at age three years) and the time series of Station 27 temperature and salinity (top panel) and recruitment verses the NAO anomaly (bottom panel) (Adopted from Colbourne and Anderson 2002).