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A Preliminary Review of Environmental-stock Relationships for Some Species of Marine Organisms in NAFO Waters of the Northwest Atlantic

by

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Abstract

Oceanographic observations are routinely collected and complied by fisheries laboratories in NAFO member countries in the northwest Atlantic, either by directed oceanographic surveys or as part of stock assessment surveys. Many studies have suggested that variations in the physical ocean environment influence the production of marine organisms, therefore the integration or incorporation of environmental information in the fishery resource assessment process is a pressing issue. To date however, environmental information for the most part is only used qualitatively, at best, in the assessment process. In this manuscript we present a review and short description of environmental-stock relationships for some marine species of fish and invertebrates in Newfoundland Shelf waters. A full statistical evaluation including their predictive powers is not included here, nor is the review considered complete. However, the information should provide a starting point to establish associations between the environment and indices of marine production.

Introduction

The past several decades have been a time 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)

The integration of environmental and process information into various stock assessments in a quantitative manner is a pressing issue and one that is receiving greater attention in recent years (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). To date however, 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 in the Northwest Atlantic (Reddin and Friedland, 1993). Generally however, the effort to date has been restricted to general 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 some recent invertebrate assessments, environmental-stock relationships have been presented and discussed in more detail and some preliminary attempts at predictive modelling were attempted. The result of this effort was one of the indicators that formed the basis of the outlook for the stock that is normally included in a spreadsheet summary of the status of some stocks, the so-called 'traffic-light' approach.

One of the first steps towards the integration of environmental information into stock assessments are to establish associations or correlations between environmental signals and trends in production indices of various fish and invertebrate stocks and to explore the predictive powers of models using environmental signals. This should eventually lead to the inclusion of both physical and biological information in process orientated effects, which would account for variations in primary and secondary production in ecosystem models. The purpose of the current manuscript is to provide a review and short description of environmental-stock associations for as many species as possible for Newfoundland waters. A full statistical evaluation including their predictive powers is not included here. Furthermore, this analysis is only intended as a starting point to establish the extent of associations and correlations between the environment and indices of marine production. In many cases the time series are too short to offer the statistical significance necessary for statistical auto-regressive type modelling.

Data Sources

The data utilized in this paper were derived from the following sources; (1) spring and autumn bottom trawl surveys by the Canadian Department of Fisheries and Oceans, (2) annual oceanographic monitoring surveys along standard sections (Fig. 1), (3) large-scale surveys of the pelagic environment on the Newfoundland Shelf, (4) commercial fisheries data and (5) counts of Atlantic salmon returning to Newfoundland rivers. Collectively, these surveys provided a comprehensive oceanographic data set for most regions of the Newfoundland Shelf with good temporal and spatial coverage for most of the decades since the 1950s.

Canada has been conducting stratified random ground fish trawl surveys on the Newfoundland Shelf in NAFO Div. 2J3KLNO since the early-1970s. Each area was stratified based on the depth contours from available standard navigation charts. Areas within each division, within a selected depth range, were divided into strata and the number of fishing stations in each stratum was allocated based on an area weighted proportional allocation (Doubleday, 1981; Bishop, 1994; Murphy, 1996). Surveys have been conducted in both the spring and fall in Div. 3L, 3N and 3O. In spring the surveys were conducted in 3L from 1971-2002, except 1983 and 1984, in Div. 3NO from 1971-2002, except 1983 in Div. 3N and 1972, 1974 and 1983 in Div. 3O, in water depths to 366 m in most years and more recently to 548 m. Surveys were conducted in the fall in 3L from 1981-2001, in 3N from 1990-2002 and in Div. 3O from 1990-2001. Since the fall of 1995 the research vessel surveys have used the Campelen 1800 shrimp trawl, thus enabling a multi-species assessment. 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. The random stratified fish samples obtained from these surveys form a basis to determine recruitment and population abundance for demersal fish stock assessments and more recently for the assessment of invertebrates.

Oceanographic measurements along standard sections and stations (Fig. 1) on the Newfoundland and Labrador Shelves have been made since the 1940s by the Biological Board of Canada and later under the auspices of the International Commission for Northwest Atlantic Fisheries (ICNAF, 1978) by several countries and currently for the Northwest Atlantic Fisheries Organization (NAFO). Additionally, as part of an expanded Canadian Atlantic zonal oceanographic monitoring program (AZMP) some of these sections are now sampled on a seasonal basis (Therriault *et al.*, 1998). Additional hydrographic, meteorological and sea ice data are obtained from a variety of sources including research studies, ships-of-opportunity and from fishing vessels. 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.

Results

Many physical and biological interactions in the marine ecosystem are considered 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 the remainder of this document we present a review and short description of environmental-stock relationships for some species of marine and anadromous fish and invertebrates in Newfoundland waters. A full statistical evaluation including their predictive powers is not yet completed and as mention above, some of the existing time series are too short to allow statistical modelling. However, when clear associations with environmental signals are evident they are included. The results presented below from various studies show time series of environmental indices and indices of various aspects of fish and invertebrate survival and production. Many of these time series show long-term trends that coincide in the physical and biological environment however on an annual basis these correlations often break down or are not statistically significant. The present analysis is intended to provide a starting point and to establish associations and correlations between the environment and indices of marine production. Once clear significant associations or correlations are made it may then be possible to focus the research necessary to understand the cause and effect mechanisms whereby environmental effects are clearly understood.

Invertebrates

Snow Crab (Chionoecetes opilio)

Recruitment in 7 of 15 commercially important crab stocks in the Bering Sea and Gulf of Alaska appears to be related to decadal climate shifts (Zheng and Kruse, 2000). Strong year classes in those king and tanner crab stocks 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 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 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 was a significant parameter in the model. Model projections indicate CPUE may begin to decline in the near future, due to warm conditions since 1995, but forecasts are associated with very broad confidence intervals.

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 for each year. The CPUE time series 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. 3). The strongest correlations 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. 3 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. This information was then used in an auto-regressive model, which predicted the observed values of the CPUE with confidence intervals and the lag correlation with the environment was used to project a 6-year forecast. The predictions of annual CPUE were close to observed values and the 6-year forecast ranged from stability of high CPUE, or at worst a 50% decline over the next few years.

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 4. The temperature time series shows the most significant association 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 warm conditions early in the life cycle are somehow favorable for production or early survival for lobster within the inshore environment of Newfoundland.

Short-finned Squid (*Illex illecebrosus*)

The short-finned squid is distributed from off central Florida to southern Labrador (Dawe *et al.,* 2000). It has an annual life cycle that includes an initial oceanic phase before it moves onto the continental shelf between the Northeastern USA and Newfoundland and southern Labrador. Seasonal migrations and annual trends in abundance are closely related to environmental variation, as is typical of most short-lived pelagic squids. Data on commercial catches from Canadian fisheries date back to 1920, but the time series is affected by market-related changes in fishing effort levels. To approximately account for this effect, catches are expressed as a proportion of the maximum within each of three consecutive periods (pre-1953, 1953-1969, and 1970-2001). Time series of fishery-independent catch rates (number/tow) are available based on autumn surveys on the northeast USA shelf since 1967 and based on July surveys on the Nova Scotian shelf since 1970 (Hendrickson *et al.,* 2001).

Trends in Canadian annual catches were inversely related to the North Atlantic Oscillation, but directly related with a bottom water temperature index at Newfoundland (Fig. 5). A direct relationship was also apparent between northeastern USA autumn survey catch rates and latitudinal displacement of the Shelf-Water and Slope-

Water front (Fig. 5 bottom panel). Correlation analysis indicated strong relationships among meteorological and oceanographic variables. Time series analysis was carried out using both catch and survey indices as dependent variables, and several environmental indices as input variables, in auto-regressive models. Overall, the models indicated that short-finned squid abundance is positively related to a favorable oceanographic regime associated with a negative North Atlantic Oscillation (NAO) index (weak winter northwesterly winds), high water temperatures off Newfoundland and a southward shift in the position of the boundary between the shelf waters and the offshore slope waters. Environmental relationships with squid indices are believed to reflect effects of broad-scale winter atmospheric circulation patterns on Gulf Stream dynamics, which largely regulate year-class strength of the dominant winter-spawning group early in life.

Atlantic cod *(Gadus morhua)*

Grand Bank (3NO)

The southern Grand Bank cod stock (NAFO Div. 3NO) occupies one of the warmest habitats anywhere along the Newfoundland Shelf. Ocean climate variability forced by atmospheric forcing (NAO) affects the bottom habitat of this region at shorter time scales than perhaps the deeper northeast Newfoundland Shelf (NAFO Div. 3K). As a result the Div. 3NO region experiences more extreme climate variations with temperatures ranging from near 0^{o}C during very cold years up to 7-8^{o}C during the warmest years (1999 for example). It is reasonable to expect therefore that fluctuations in water properties in this area may influence the recruitment and growth of many demersal fish species. Recruitment for the Div. 3NO stock, defined as the abundance of cod at three years of age was estimated using VPA ADAPT framework (Stansbury *et al.*, 1999). Recruitment for the Grand Bank cod stocks experienced long-term declines during the 1970s until the middle to late-1980s from the highs of the early- to mid-1960s (Fig. 6). Superimposed on the long-term trends were short-term annual variations. By the early-1990s recruitment in this stock was in a steep decline and throughout the 1990s it remained at historically low levels (Fig 6). Coincident with the changes in cod recruitment on the Grand Bank ocean temperatures and water salinity measured at Station 27 during the past several decades have experienced near-decadal oscillations superimposed on a general downward trend (Fig. 6). 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. 6 bottom panel).

The thermal habitat for Atlantic cod in the Div. 3LNO region has shifted from mainly cold $<0^{o}$C conditions of the early-1990s to a relatively warm environment from 1998 onwards with approximately 60% of the bottom covered with water $>2^{o}$C by the fall of 1999. Since the spring of 1998 up to the spring of 2000 there was a significant increase in the number of cod caught per tow in survey sets in Div. 3NO. Also larger catches were more widespread in shallower water on top of the bank, mainly in water with temperatures above 2^{o}C (Colbourne and Murphy, 2000). The mean bottom temperature increased gradually from the low ($<0.5^{o}$C) in 1990 to about 1^{o}C by 1997 and to 2^{o}C by 1999. The increase in Div. 3NO catches beginning in 1997 coincides with the increase in bottom temperature (Fig. 7). The cod number and catch weighted temperature distributions show the distribution of cod is associated with the warmer portion of the available temperature range (Colbourne and Murphy, 2000).

There are several possible reasons for these observations. There are obvious signs of improved recruitment in Div. 3NO as a significant portion of the increase in catch numbers during the surveys is comprised of fish age 3 years and less. Also, during 1998 and 1999 a significant increase in the abundance of o-group Atlantic cod was sampled in the region (Dally *et al.*, 2000). It appears that the recent increase in water temperature in the area may have made the southern Grand Bank a more suitable environment for cod spawning and possibly improved survival rates. The increase in catch per tow in Div. 3O was most obvious in the spring of 1998 close to the Subdiv. 3Ps boundary. These increases have become more easterly distributed in subsequent surveys. It is possible that this is a result of range expansion from the adjacent Subdiv. 3Ps stock as a result of a more favorable environment on the Grand Bank, either for cod or their prey, or both. Also the apparent increases may be the result of a temperature dependent increase in catchability or related to other biological or environmental factors such as increase in prey species or a shift to a more suitable environment for prey species.

St Pierre Bank (3Ps)

Assessments of the cod stock in NAFO Subdiv. 3Ps have indicated a steady decline in biomass from the peak in 1985 to a minimum in 1992 followed by an increase during 1993-1997 after the implementation of a fishing moratorium. Recruitment also experienced a general decline since the early 1980s remaining at historical low values during most of the 1990s with slight increase during 1999-2000 (Brattey *et al.*, 2000). The near-bottom habitat in the Subdiv. 3P region consists of two distinct oceanographic regimes. One influenced by cold-fresh water from the eastern Newfoundland Shelf, which includes much of St. Pierre Bank and regions to the east. In this region temperatures generally range from 0-2°C but are often <0°C in many years. The other regime includes the deeper regions of the Laurentian and Hermitage Channels and areas to the west of St. Pierre Bank. This region appears to be influenced mostly by warmer shelf slope water from the south.

The most evident trend in the number of cod caught per set during recent surveys was the increasing number of zero catches in the colder <0°C water on St. Pierre Bank and eastward, mainly from 1985 to 1998. During 1999 and 2000 larger catches became more wide spread over St. Pierre Bank region as cold <0°C water disappeared from the area (Colbourne and Murphy, 2002). Variations in the mean number of cod per set for strata with water depths <100 m are correlated with the changes in the thermal habitat on St. Pierre Bank (Fig. 8). However there is no significant correlation between bottom temperatures and the mean numbers of fish caught per set for strata in water depths >100 m. The low numbers of cod caught per set from the mid-1980s to the mid- to late-1990s correspond to extremely low bottom temperatures on St. Pierre Bank during the same time period. The increase in the number of cod per set on St. Pierre Bank and the increase in the number of non-zero catches in the eastern regions, corresponding to the near-record high bottom temperatures during 1999 and 2000 also indicates a preference of cod towards a warmer habitat. The extreme variations in the catch rates on St. Pierre Bank may also be due to a temperature dependent increase in catchability or related to other biological or environmental factors such as increase in prey species or a shift to a more suitable environment for prey species (Colbourne and Murphy, 2002).

Yellowtail Flounder *(Limanda ferruginea)* (3LNO)

Recent assessments have indicated a significant increase in the biomass and abundance of yellowtail flounder on the Grand Bank beginning in 1995 from the relatively low and declining estimates of the early-1990s. These increases have continued during the latter half of the 1990s reaching record levels in 1999. In addition, the population has also expanded it's range onto the northern Grand Bank in Div. 3L (Walsh *et al.*, 2000). In recent years the centroid of the biomass of yellowtail flounder has been located within Div. 3NO centred over the southeast shoal of the Grand Bank. This area corresponds to the warmest bottom temperatures found anywhere on the Newfoundland Shelf. Spring bottom temperatures in this region range from a minimum of 1-2°C during cold years (1990) to 3-4°C during warm years (1998 and 1999). While the abundance of yellowtail flounder in this region was significant from 1990-1995, there was a sudden increase in catch rates during the fall of 1995 and these rates continued to increase from 1997 to 2000. During this time period the spatial extent of larger catch rates also expanded as the area of >0°C water covered the entire Div. 3NO region.

Time series of the mean bottom temperature and the mean relative number and weight of yellowtail for the survey are shown in Fig. 9 for the spring and fall surveys. During the spring the mean bottom temperature increased gradually from the low (<0°C) in 1990 to >1.5°C by 1999. Correspondingly, the percentage area of the bottom covered with water <0°C decreased from >60% in 1991 to <10% in 1999. The increase in both the mean number and weight of yellowtail during spring and fall coincides with the change in the thermal habitat around the mid-1990s. In addition, the total catch continued to increase from the mid-1990s up to 1999 as bottom temperatures in the region continued to increase. From 1990 to 1994 the abundance of yellowtail flounder remained at a near constant level, however beginning in 1995 both the abundance and average weight of the catches per set increased significantly.

The sudden increase in catch rates coincided with both a significant increase in bottom temperature and with the implementation of the new Campelen 1800 shrimp trawl, which is more efficient at catching smaller fish. From 1997 to 1999 the mean number and weight per set continued to increase as the mean bottom temperature increased further to a maximum in 1999. The spatial extent of larger catches and smaller non-zero catches in both Div. 3L and 3NO also increased as the area of warmer water covered an increasingly larger area of the region. For example, catches in Div. 3L during the spring of 1999 reached its most northern extent in recent years with non-zero catches above 47°N, coinciding with the warmest water on the Grand Banks since the early-1980s. The striking similarity between the trends in the mean bottom temperature and both the average numbers and weight per set may indicate a temperature dependent increase in catchability in this species (Colbourne and Bowering, 2001).

Atlantic salmon *(Salmo salar)*

Marine survival

The ratio of Atlantic salmon smolt production and subsequent adult small salmon returning to various rivers can provide a measure of or estimate of marine survival presumably due to natural mortality in the absence of a commercial fishery. Information on smolt production and returning adult salmon counts is available from six rivers in the Newfoundland Region (O'Connell *et al.*, 2001). These data were used to construct a composite index of survival for all six rivers. The survival index is based on returns of small salmon, mainly one-sea-winter fish, and the numbers are not adjusted for marine exploration during years with a commercial fishery. The composite index shown in Fig. 10 was constructed by adding by year the number of smolts and small salmon across all six rivers. The index was then standardized by subtracting the overall mean value from each year and dividing by the standard deviation.

In general while there are some trends in the series the survival is highly variably between years with negative anomalies in 4 out of the past 5 years. Also shown in Fig. 10 are time series of Station 27 surface temperature, an inshore temperature time series at Comfort Cove on the northeast Newfoundland coast and the area of cold intermediate water on the southern Labrador Shelf. In general, there is a strong association between the environmental variables with the survival anomalies at time lags of 0 and 1 year, indicating a possible environmental influence on survival, either directly on departing smolts or on the at-sea survival rates of small salmon. Time periods of high positive survival anomalies are associate with generally warm ocean conditions, particularly during the early part of the time series. During the more recent years (1997-2000) while the ocean warmed considerably, the corresponding increase in survival was marginal, but nevertheless did show a slightly increasing trend. In 2001 however, the decrease in survival to below normal values was much larger that what would be expected based on environmental trends, indicating perhaps, other confounding factors influencing salmon survival.

The run timing

An additional example of linkages between environmental conditions and fish stocks includes ongoing work examining spatial and temporal variation in migration timing of adult Atlantic salmon (J. B. Dempson). Run timing is an adaptation to local environmental conditions, and in some species is a heritable trait linked with the overall life history of the species. Objectives of this program are to: 1) examine variation in adult Atlantic salmon run timing among geographic regions; 2) examine variation in run timing among rivers within geographic regions; 3) describe temporal variation in run timing within rivers; and 4) examine linkages of temporal variation with various environmental parameters. The latter objective also includes developing a composite index of salmon run timing from 17 rivers over a 15-year interval (1986–2000). With respect to objective 4) above, environmental indices included in this study are Newfoundland spring air temperature anomaly, Station 27 surface and depth averaged spring temperature anomaly, and the aerial extent of Newfoundland Shelf sea ice during the winter and spring time periods.

Randomization tests were used in determining statistical significance among relationships. Preliminary analyses indicate that adult salmon run timing varies significantly among regions, among rivers within geographic regions, and among years within rivers. For salmon <63 cm in length, median run timing can vary by as much as 4.7 weeks among years in some rivers. Results from associations of median run timing with environmental variables indicate significant correlations with spring air temperature anomaly ($r=-0.587$ $p=0.010$), Station 27 near-surface temperature ($r=-0.825$ $p=0.00$) (Fig. 11 top panel), Station 27 integrated temperature ($r=-0.822$ $p=0.000$) and the aerial sea-ice extent (April – June) ($r=0.727$ $p=0.002$) (Fig. 11 bottom panel). A positive run-time index coincides with salmon runs being later, while a negative index infers earlier run timing. As shown in Fig. 11 warmer environmental conditions generally correspond to an earlier run of salmon to Newfoundland rivers. These and other relationships suggest that over broad geographic scales, Atlantic salmo n run timing is influenced, in part, by interannual variation in atmospheric and oceanic climate conditions.

The Pelagic O-group Environment

The pelagic ecosystem responded in several ways to the changing physical environment on the Newfoundland Shelf during the 1990s. The abundance of individual species of o-group pelagic fish remained low from 1994 to 1997. However, beginning in 1998 a dramatic increase in abundance occurred for several species on the Grand Banks including Atlantic cod, sandlance (*Ammodytes* sp.), redfish (*Sebastes* sp.) and American plaice (*Hippoglossoides platessoides*). Atlantic cod remained at relatively low levels of abundance on the Grand Banks until 1997 after which it increased by at least two orders of magnitude in 1998 and 1999 (Fig. 12). During this time period the spatially-averaged bottom temperature on the Grand Bank during the spring increased from near 0^oC in 1994 to over 1^oC in 1998 and to over 1.5^oC by the spring of 1999 (Fig. 12). The large increase in pelagic fish abundance, which first appeared over the Grand Banks in 1998, was detected further northward along the northeast coast of Newfoundland in 1999 as warm ocean conditions progressed northward. In contrast, the abundance of o-group Arctic cod (*Boreogadus saida*) decreased from 1994 to 1999, and this decrease was associated with the increasing bottom temperature observed on Hamilton Bank on the southern Labrador Shelf (Fig. 13).

In the early-1990s, the estimated biomass of invertebrate zooplankton, primarily copepods, was at a relatively low level but increased by a factor of two after 1996. *Calanus finmarchicus*, considered the dominant zooplankton organism in the temperate North Atlantic increased in abundance throughout the 1990s with maximum values recorded in 1999 (Fig 13). This increase appears to be a direct response to warm water conditions following the cold period of the early-1990s. The increase in nekton biomass occurred first in the south, over the Grand Bank, in 1998 and then extended to the north in 1999 as ocean temperatures continued to increase. Across the whole survey area several fish components of the pelagic ecosystem declined in abundance during the first half of the 1990s. Since these observed minima, all species except Arctic cod increased in abundance by approximately two orders of magnitude, representing a system wide response across species lines. This indicated that Arctic species were being replaced by boreal and temperate species such as capelin and sandlance during the warm years of the late-1990s. Furthermore, these observations are consistent with the expected biological response of the pelagic ecosystem to a warming ocean environment (Anderson *et al.,* 1999, Dalley *et al.,* 2000;, Colbourne and Anderson, 2002).

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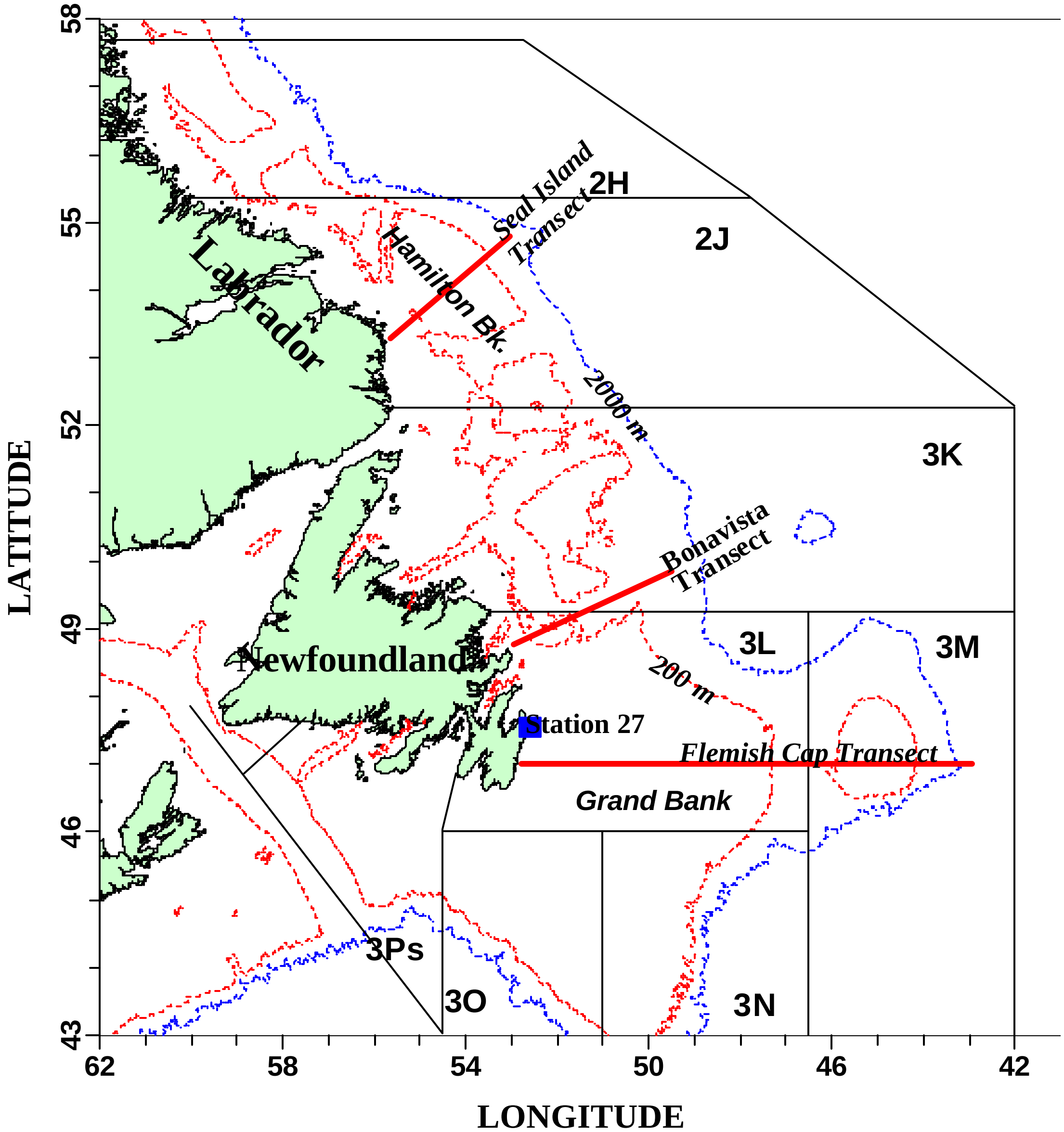


Fig. 1. Regional map showing the positions of standard monitoring transects, Station 27 and the statistical fish management areas established by the Northwest Atlantic Fisheries Organization (NAFO).

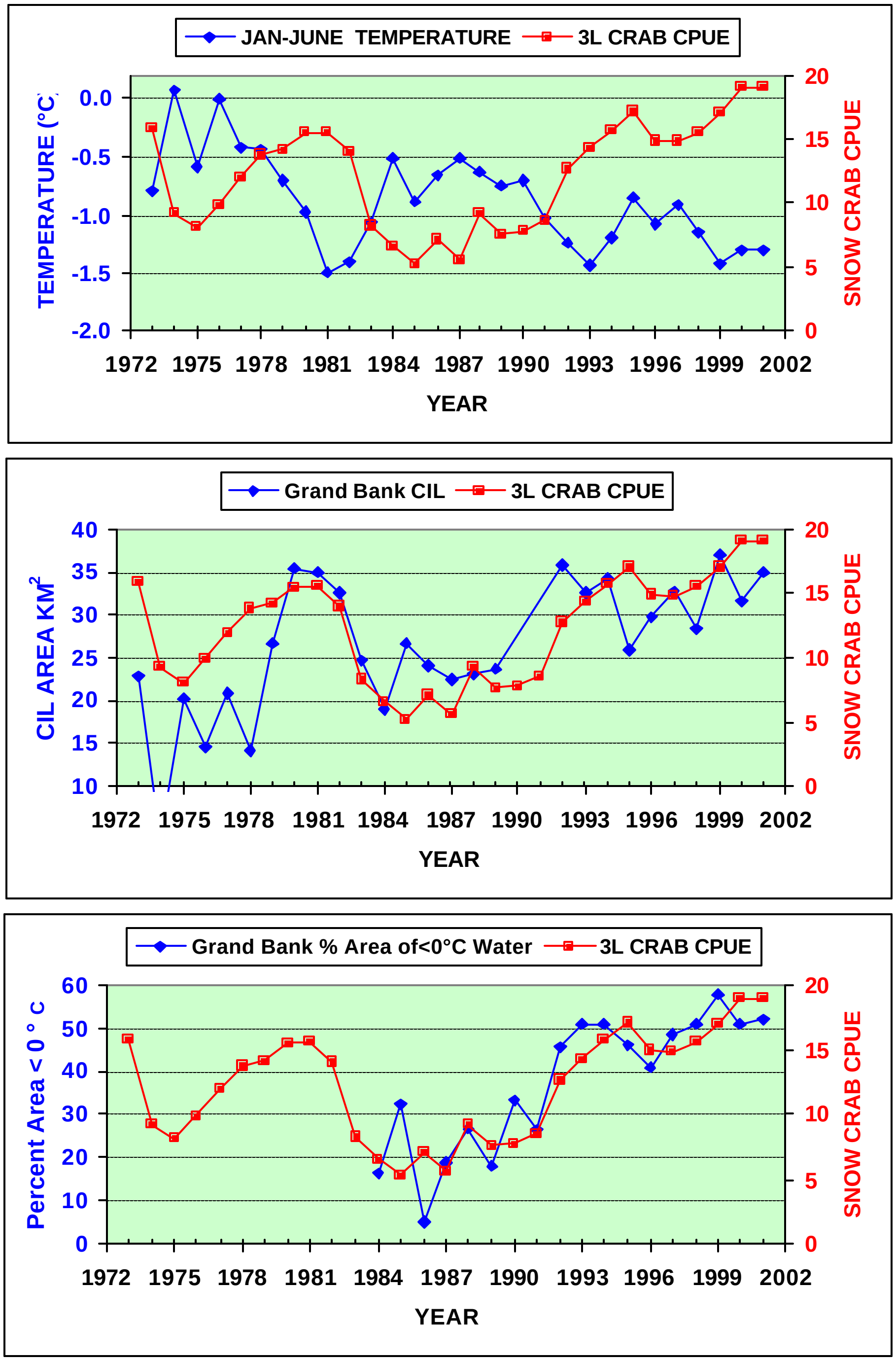


Fig. 2. Annual CPUE of snow crab in NAFO Div. 3L and the time series of Station 27 temperature, Grand Bank CIL area and the % area of the bottom covered by <0°C water on the Grand Bank.

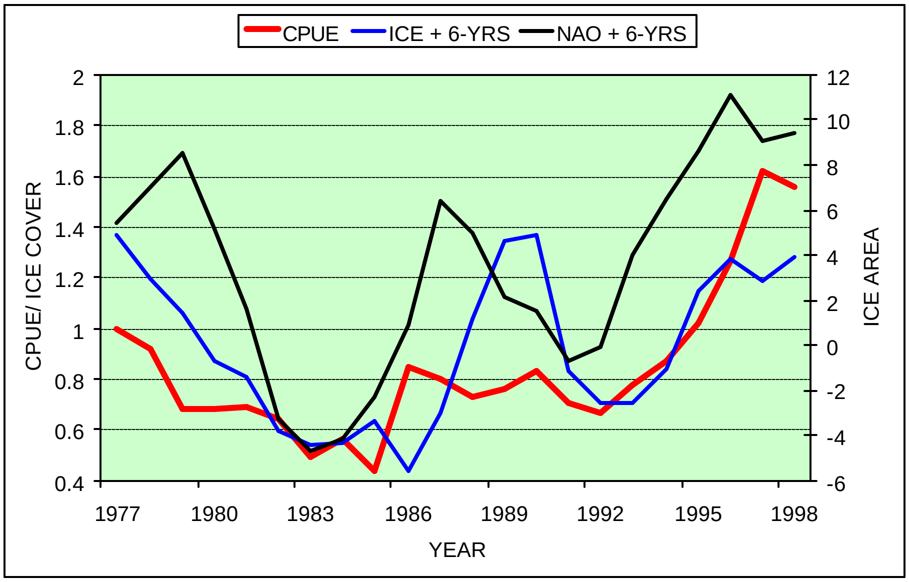


Fig. 3. Annual CPUE of northern shrimp in NAFO Div. 2GH and the time series of the areal extent of sea ice on the Newfoundland and Labrador Shelf and the NAO.

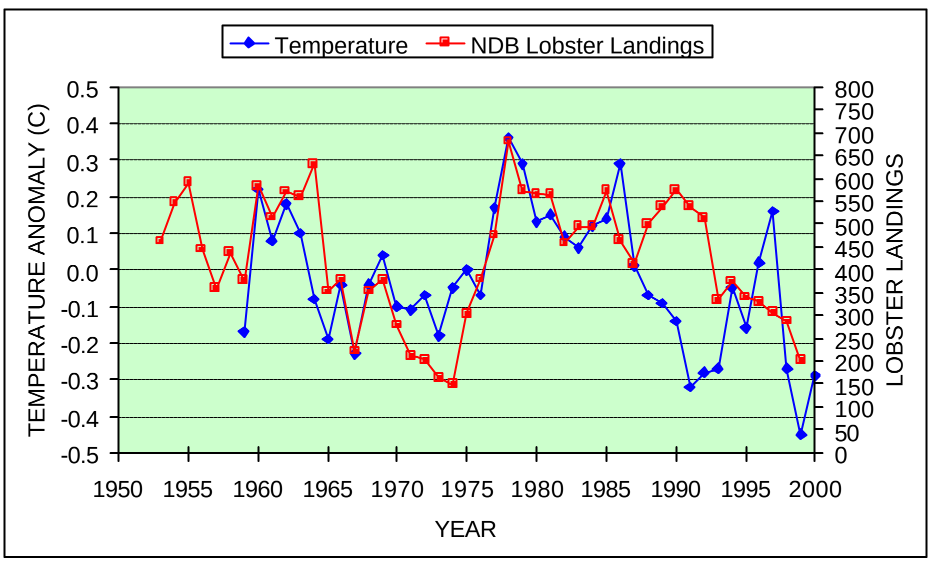


Fig. 4. Annual lobster landings on the northeast Newfoundland coast NAFO Div. 3K and the time series of Station 27 50 m depth temperature.

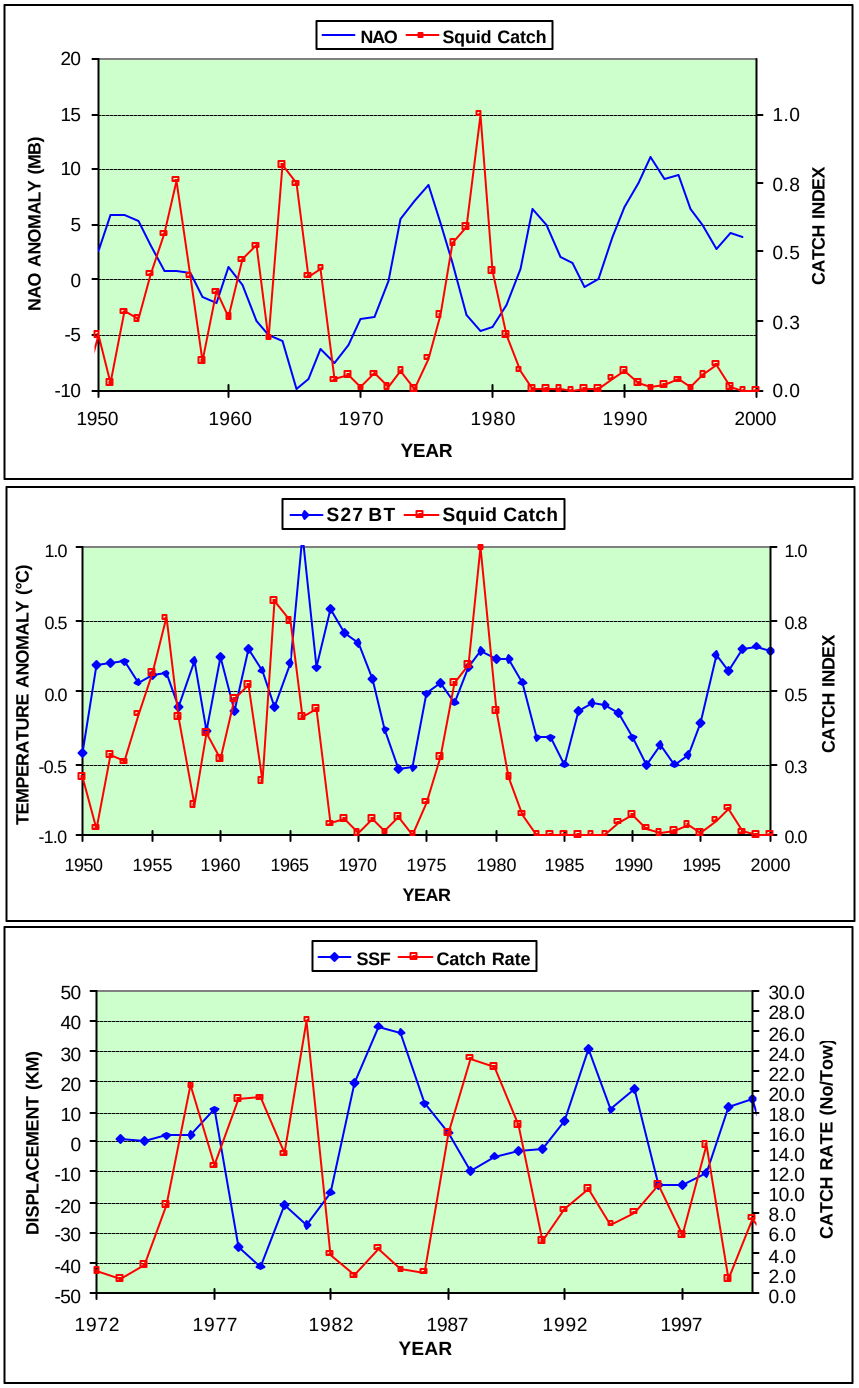
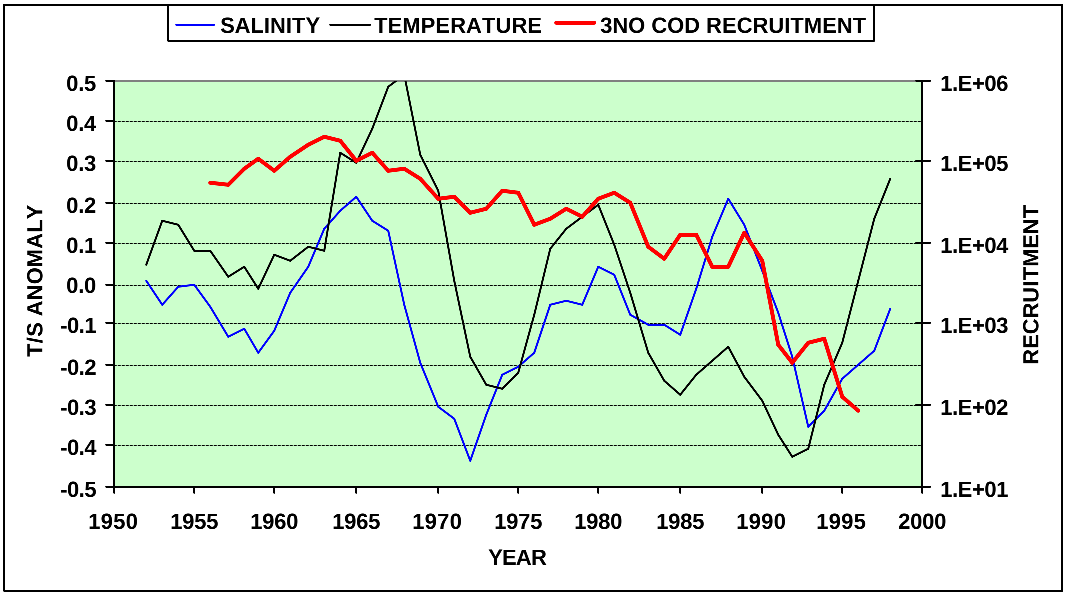


Fig. 5. Indices of Canadian and USA short-finned squid catch rates and time series of the NAO, Station 27 temperature and the displacement of the shelf-slope-front.



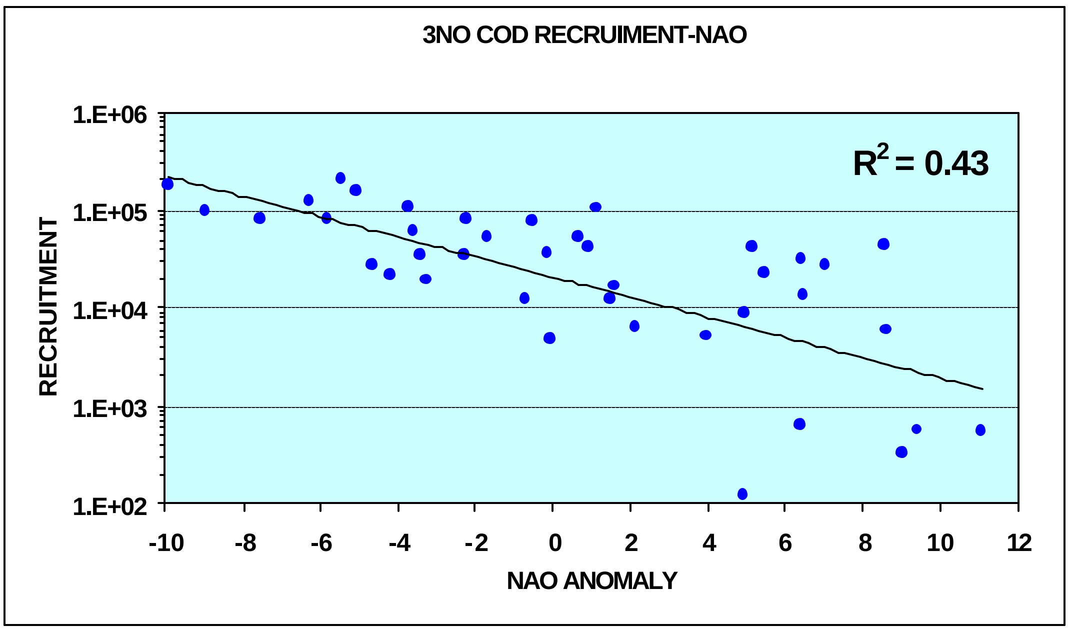


Fig. 6 Recruitment in Grand Bank (Div. 3NO) cod from Sequential Population Analysis (defined as abundance estimated at age three years) and the time series of Station 27 temperature and salinity (top panel) and recruitment verses the NAO anomaly (bottom panel).

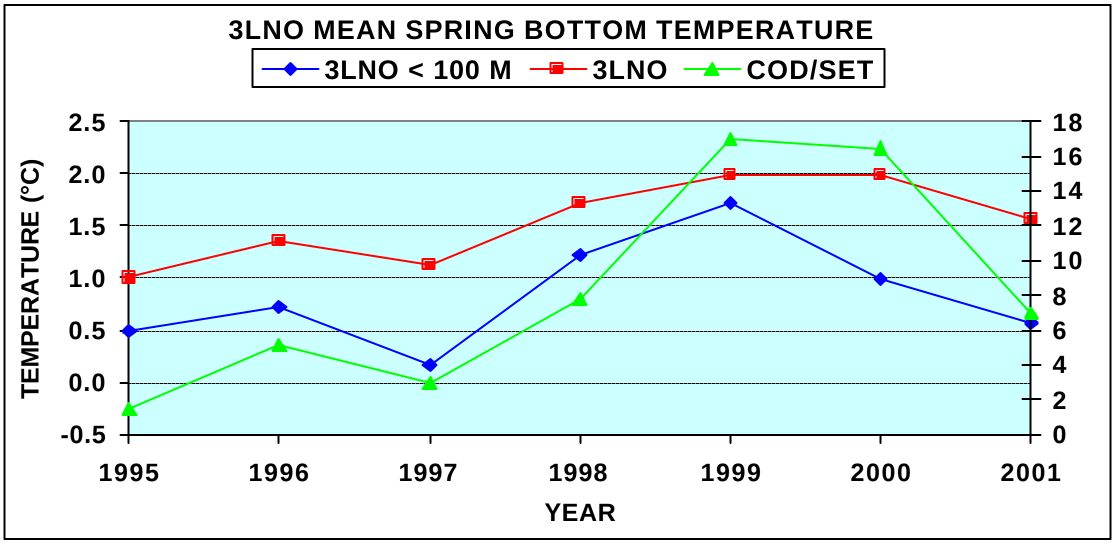


Fig. 7. Time series the mean bottom temperature and the mean numbers of cod per set for the spring survey in NAFO Div. 3NO.

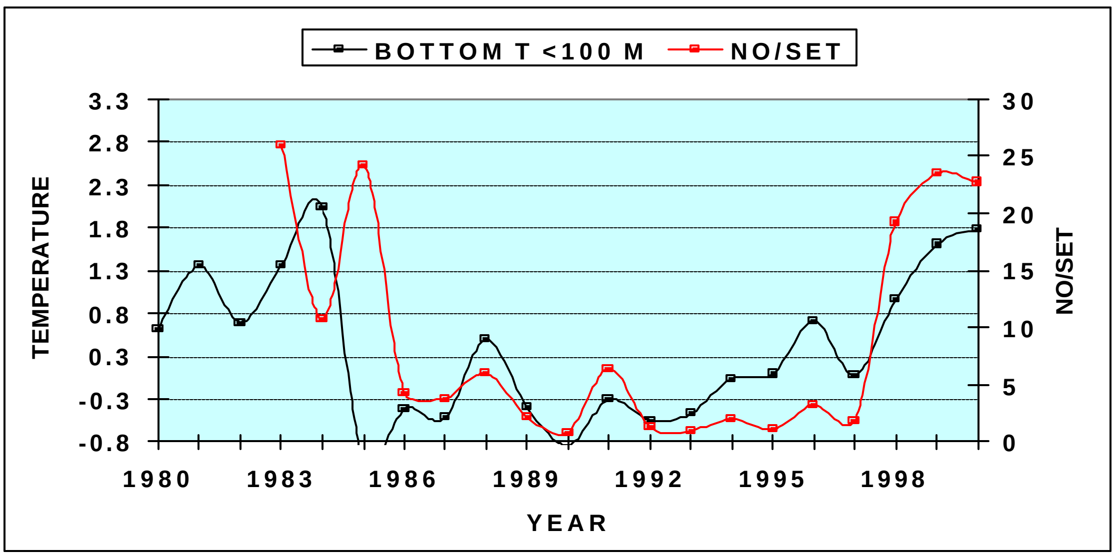


Fig. 8. Time series the mean bottom temperature and the mean numbers of cod per set for the survey in NAFO Subdiv. 3P for strata with water depths <100 m.

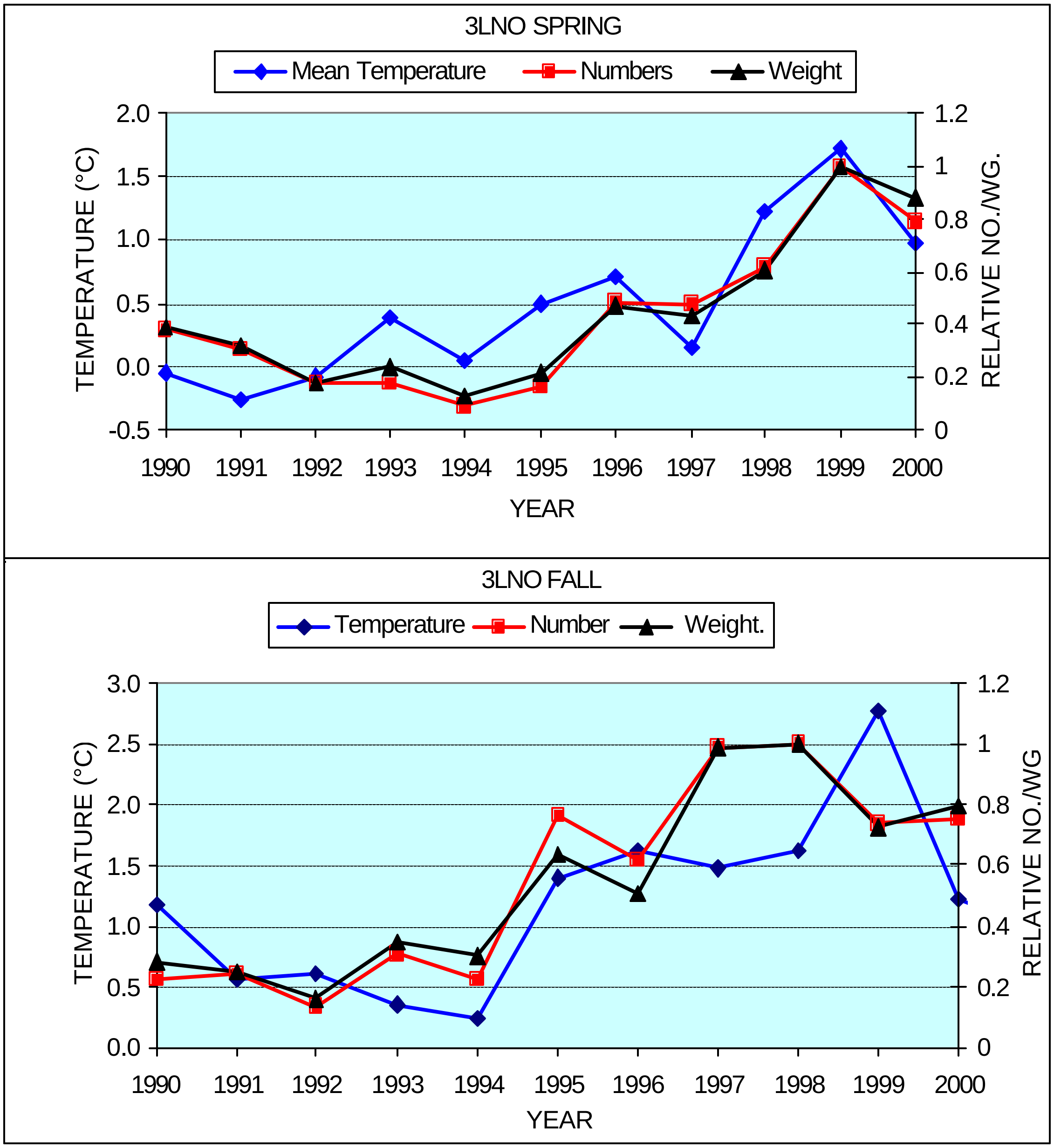


Fig. 9. Time series of the mean bottom temperature and the mean relative numbers and weight of yellowtail caught per set for the spring (top panel) and fall surveys (bottom panel) for NAFO Div. 3LNO.

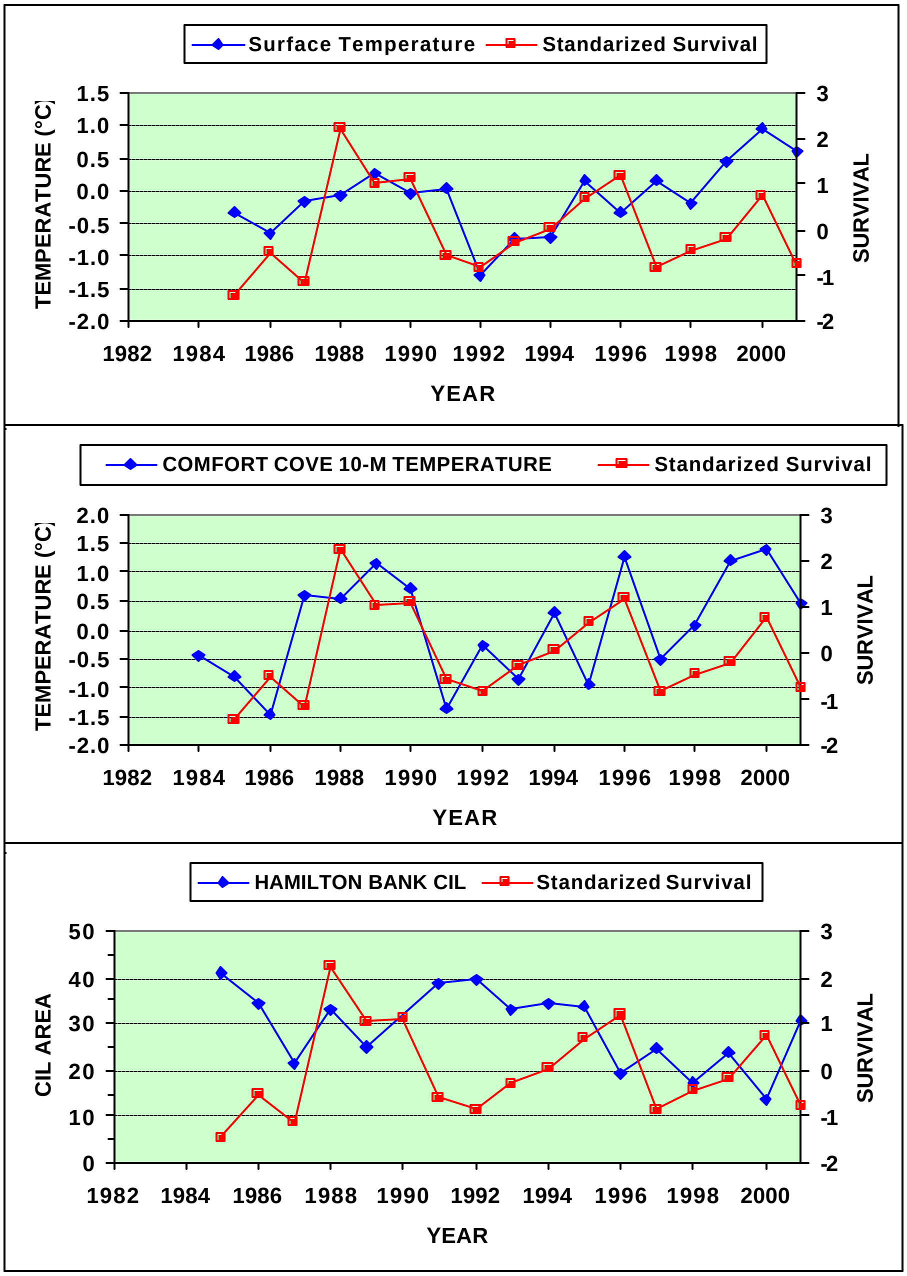


Fig. 10. Annual survival indices of Atlantic small salmon for several rivers in Newfoundland and the time series of Station 27 surface temperature, northeast Newfoundland coast near-surface temperature and the southern Labrador Shelf area of CIL water.

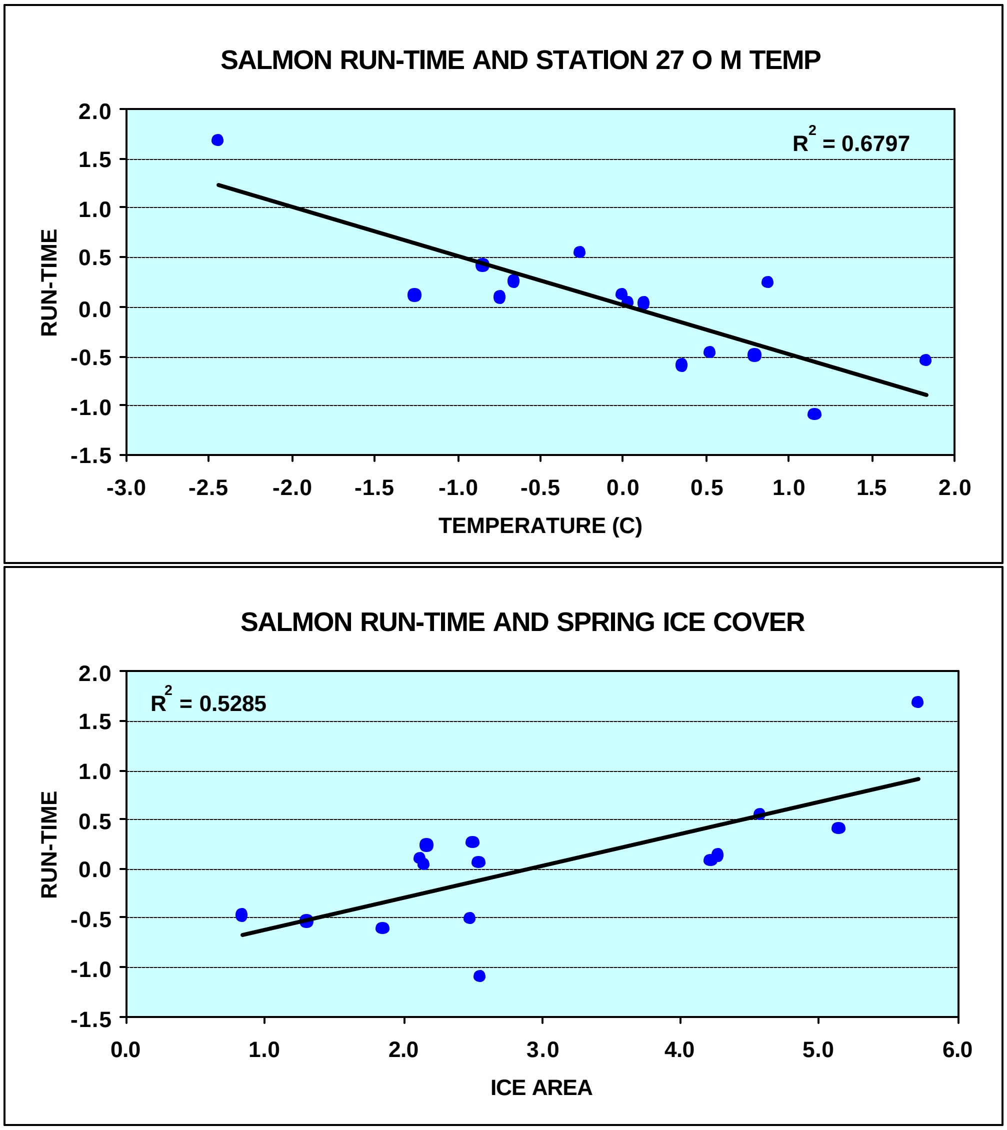


Fig. 11. The correlation between Atlantic adult salmon run-time for several rivers in Newfoundland and Station 27 surface temperature and Newfoundland and Labrador sea-ice cover.

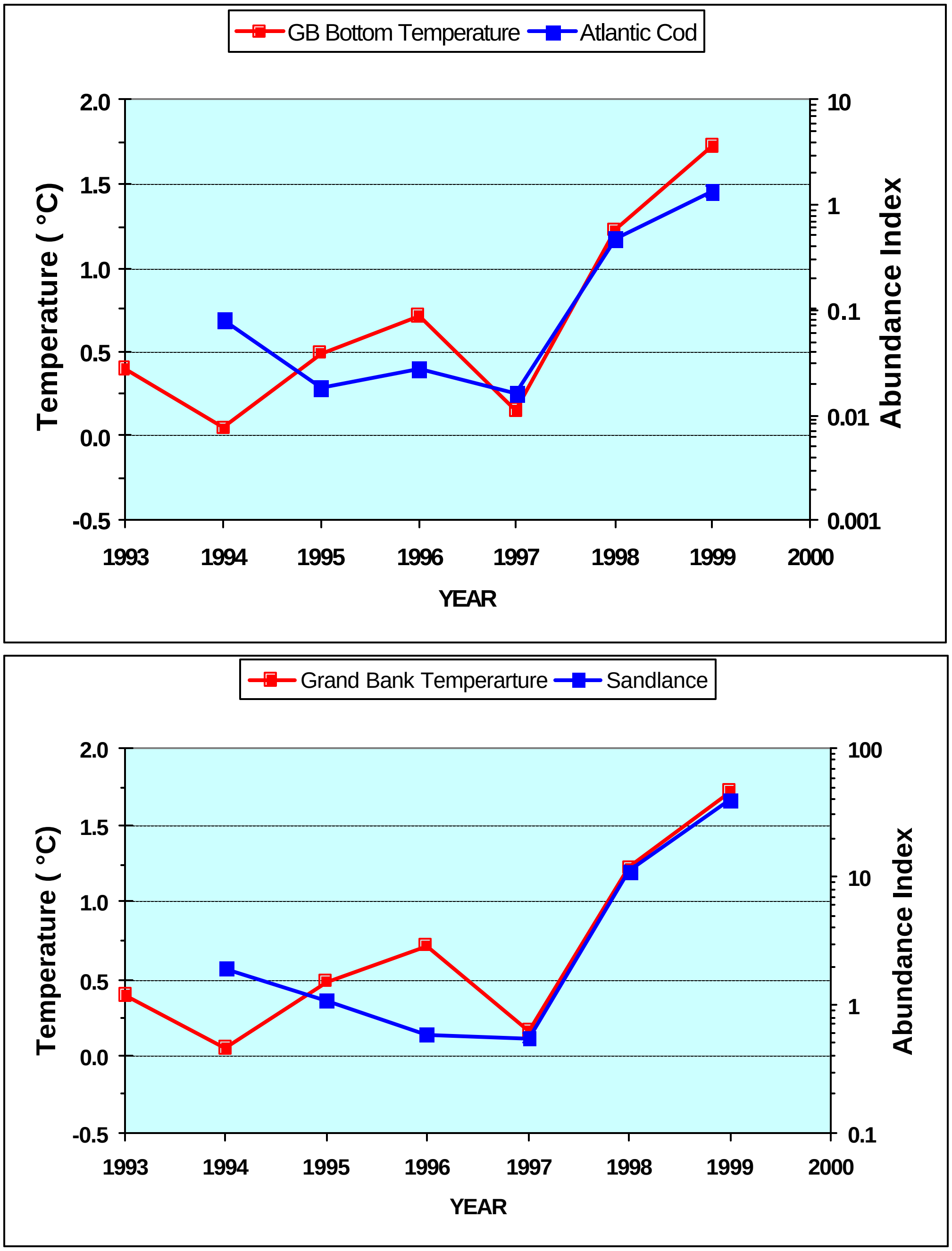


Fig. 12. Recent trends in the relative abundance of pelage o-group Atlantic cod (top panel) and sandlance (bottom panel) and the spatially averaged spring bottom temperature (in °C) for the Grand Bank.

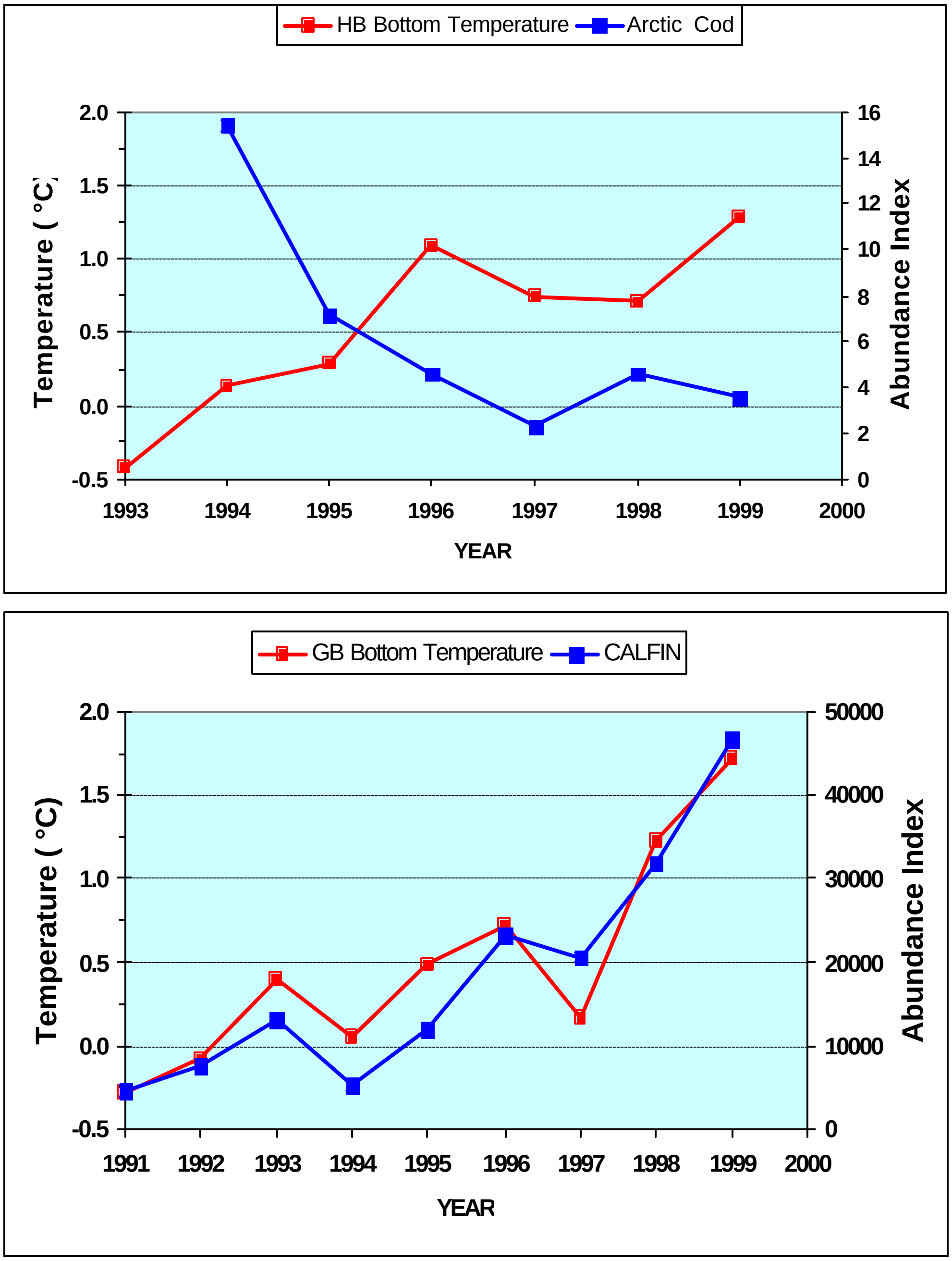


Fig. 13. Recent trends in the relative abundance of pelage o-group Arctic cod and the spatially averaged fall bottom temperature (in °C) for Hamilton Bank (top panel) and the relative abundance of *Calanus finmarchicus* together with the spatially averaged spring bottom temperature (in °C) for the Grand Banks.