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Predicting the future of marine fish and fisheries off Labrador and eastern Newfoundland under scenarios of climate change; information and thoughts for the Arctic Climate Impact Assessment (ACIA)

Prédiction de l'avenir des poissons marins et de leur pêche au large du Labrador et de l'est de Terre-Neuve en fonction des scénarios du changement climatique; informations et précisions pour l'Évaluation des incidences climatiques dans l'Arctique (EICA)

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Abstract

This paper is an initial step in the process of providing predictions regarding the potential impact of climate change on the marine fish and fisheries of northeastern Canada. The exercise, which is undertaken as part of the Arctic Climate Impact Assessment (ACIA), entails an overview of the major fisheries from Davis Strait to the northern Grand Bank, focussing on a brief history of the landings and a discussion of factors that are known or suspected to have been important in determining changes in both landings and stock status. One would like to use relationships derived from the history of changes in the physical environment and various aspects of fish biology (distribution, recruitment, growth, mortality) to predict how each species might respond to oceanographic changes that might accompany climate change, but this is difficult for several reasons. First, as with fisheries elsewhere, it is difficult to distinguish the influence of climate variability from the influences of fishing and biological interactions among species. Thus, there are few robust demonstrations of the influence of climate variability. Second, the ecosystems of the Labrador Shelf, Northeast Newfoundland Shelf and northern Grand Bank have changed so dramatically in the past few decades that any relationships seen in the past may no longer apply. Third, even if we had confidence that we could predict the response of fish stocks to specific changes in the physical oceanography, we lack at this time the downscaling that would translate the broadscale projections of climate change to specifics of regional physical oceanography. We invite critiques of our observations and tentative conclusions.

Résumé

Cette étude constitue la première étape du processus de prédiction des incidences potentielles du changement climatique sur les poissons marins du nord-est du Canada et leur pêche. Ce processus, qui s’inscrit dans le cadre de l’Évaluation des incidences climatiques dans l’Arctique (EICA), comporte un survol des principales pêches pratiquées du détroit de Davis à la partie nord du Grand Banc, axé sur un bref historique des débarquements et une discussion des facteurs reconnus ou présumés comme ayant joué un rôle important dans les variations des débarquements et les changements dans l’état des stocks. On aimerait utiliser les relations issues de l’historique des changements dans le milieu physique et divers aspects de la biologie des poissons (distribution, recrutement, croissance, mortalité) pour prédire comment chaque espèce réagira aux changements océanographiques qui peuvent découler du changement climatique, mais cela est difficile pour plusieurs raisons. En premier lieu, comme dans le cas des pêches pratiquées ailleurs, il est difficile de distinguer l’influence de la variabilité du climat des influences de la pêche et des interactions biologiques entre les espèces. Rares sont donc les mises en évidence robustes de l’influence de la variabilité du climat. En deuxième lieu, les écosystèmes du plateau continental du Labrador, de la partie est du plateau continental de Terre-Neuve et de la partie nord du Grand Banc ont tellement changé au cours des dernières décennies que toute relation observée par le passé peut ne plus s’appliquer. En troisième lieu, même si nous étions confiants de pouvoir prédire la réaction des stocks de poisson à des changements particuliers dans le milieu océanographique physique, nous ne disposons pas à ce moment-ci de la capacité de réduction nécessaire pour traduire les prédictions du changement climatique de grande échelle en effets régionaux sur les facteurs océanographiques physiques. Les critiques de nos observations et de nos conclusions provisoires sont bienvenues.

Introduction

The Arctic Climate Impact Assessment (ACIA) is an assessment of the consequences of climate variability and change in the Arctic. Its purposes are to evaluate and synthesize knowledge on climate variability and climate change; to examine the possible impacts of such changes on the environment and its living resources; and to provide useful and reliable information to support policy-making processes (ACIA 2002). The study started in 2000, with the final report due in late 2004. The ACIA assessment builds upon two kinds of scenarios. First, it assumes a moderate scenario for emissions (greenhouse gasses and aerosols). This is the IPCC SRES B2 scenario (IPCC 2001). It then uses climate scenarios, based on this emissions scenario, from five Atmosphere-Ocean General Circulation Models (GCM's). The climate scenarios have a baseline of 1980-1999 and projections to 2099, with particular attention directed to 20-year time slices centred on 2020, 2050 and 2080. Projections from the five models disagree on the magnitude of changes and regional aspects of those changes, but they all project that warming will be greater in the Arctic than elsewhere and that warming will be greater in winter than in summer.

One chapter of the ACIA report will describe marine fisheries and the impacts that climate change might have on them. In evaluating the impacts on marine fisheries, a regional approach has been taken, with separate sections on the Barents Sea, Iceland, Greenland, northeastern Canada, and the western and eastern Bering Sea. Each section contains a biological overview of the important species, including factors affecting their abundance and biology, followed by a discussion of the economics of the fisheries, and concluded with predictions regarding changes that might be expected for individual species and the ecosystems in which they are embedded, based on the outcomes of the five climate scenarios mentioned above.

In this document, we will not provide an overview of all the changes that might occur in the marine environment and its biota as a consequence of climate change. Such changes will be discussed in another chapter of the ACIA report, and may be found in reviews such as IRI (2001). We provide only a biological overview for species that occur in the waters off northeastern Canadian and preliminary conclusions regarding the consequences of climate change. It should be noted that these conclusions are highly speculative and may differ from the conclusions in the final ACIA report when it is published in 2004. Indeed, much of our text focuses on why it is difficult to make long-term predictions with a reasonable degree of confidence. The final section of this paper includes a number of observations and suggestions regarding initiatives that might help advance our understanding of the influence of climate change on fish and fisheries in the Labrador/Newfoundland area. We invite oceanographers, fishery biologists and managers to critique this early draft and to contribute toward making predictions that are sufficiently realistic to be of value to policy makers.

Ecosystem Dynamics

For the ACIA study, the Arctic is divided into four Sub-regions and the fisheries in ACIA Sub-region IV may be further subdivided into those near the coast of Greenland, those near the coast of Canada, and those in deep waters of Baffin Bay and Davis Strait between Greenland and

Canada. The whole Sub-region lies within the fisheries convention area of the Northwest Atlantic Fisheries Organization (NAFO), and the fish stocks are currently managed by either the coastal state or NAFO.

Along the northeast coast of Canada the ACIA study area is extended southward to the central Grand Bank (46ºN) in order to assess climate impacts on marine ecosystems that are comparable to those considered by ACIA in the northeast Atlantic and around Iceland. This extension far to the south of the other geographic areas is necessitated by the presence of the Labrador Current, which transports cold water southward from Davis Strait, the Canadian Archipelago and Hudson Bay. The median southerly extent of sea ice is on the northern Grand Bank at approximately 47º N (Anon. 2001a) and bottom water temperatures on the northern Grand Bank are below 0º C for considerable periods. The southerly extent of cold conditions is also indicated by the regular presence of Arctic cod (*Boreogadus saida*) along the northeast coast of Newfoundland and their occasional occurrence on the northern Grand Bank (Lilly et al. 1994; Lilly and Simpson 2000). In order to discuss the dynamics of Atlantic cod (*Gadus morhua*) and capelin (*Mallotus villosus*), and the fisheries exploiting them, it will be convenient to include the whole of the putative stock areas, which extend to the southern boundary of NAFO Division 3L at 46º N for the major stocks of both Atlantic cod (NAFO Div. 2J+3KL) and capelin (NAFO Subarea 2 + Div. 3KL). The Gulf of St. Lawrence is not considered in this study, even though the area is ice-covered in winter and the temperature structure of the water column is similar to that off eastern Newfoundland.

The ecosystem off northeastern Canada has been characterised by a relatively small number of species, a few of which have historically occurred in high abundance (Bundy et al. 2000; Livingston and Tjelmeland 2000; Carscadden et al. 2001). The dominant fodder fish has historically been capelin, with Arctic cod more prominent to the north and sand lance (*Ammodytes dubius*) more prominent to the south on the plateau of Grand Bank. Herring (*Clupea harengus*) is found only in the bays and adjacent waters. These four species of planktivorous fish feed mainly on calanoid copepods and larger crustaceans, the latter being predominantly hyperiid amphipods to the north and euphausiids to the south. The dominant piscivorous fish has been Atlantic cod, but Greenland halibut (*Reinhardtius hippoglossoides*) and American plaice (*Hippoglossoides platessoides*) have also been important. Snow crab (*Chionoecetes opilio*) and northern shrimp (*Pandalus borealis*) have been the dominant benthic crustaceans. The top predators are harp seals (*Phoca groenlandica*) and hooded seals (*Cystophora cristata*), which migrate into the area from the north during late autumn and leave in the spring. Other important predators include baleen whales, most of which migrate into the area from the south during late spring and leave during the autumn. Additional immigrants from the north during the winter include many birds which spend the summer in the Arctic, and additional immigrants from the south during summer include short-finned squid (*Illex illecebrosus*), fish such as mackerel (*Scomber scombrus*) and bluefin tuna (*Thunnus thynnus*), and several species of birds.

The Labrador/Newfoundland ecosystem experienced major changes during the last two decades of the 20^{th} century. Atlantic cod and most other demersal fish, including species that were not targeted by commercial fishing, experienced declines to very low levels by the early 1990s (Atkinson 1994; Gomes et al. 1995). In contrast, snow crab (DFO 2002b) and especially northern shrimp (DFO 2002c) surged during the 1980s and 1990s and now support the most important fisheries in the area. Harp seals increased in abundance from fewer than 2 million individuals in the early 1970s to more than 5 million in the late 1990s (Healey and Stenson 2000; Stenson, et al. 2002). Capelin have been found in much reduced quantities in offshore acoustic surveys since the early 1990s, but indices of capelin abundance in the inshore have not experienced similar declines, leaving the status of capelin uncertain and controversial (DFO 2000b, 2001).

The waters of eastern Newfoundland have been fished for centuries, primarily for Atlantic cod but with an increasing emphasis on other species during the latter half of the 20th century. These fisheries have undoubtedly had an influence on both the absolute abundance of some species and the abundance of species relative to one another. However, the role of the fisheries in structuring the ecosystem is often difficult to distinguish from the role of changes in the physical environment. The area experienced cooling during the last 3 decades of the 20th century, with particularly cold periods in the early 1970s, early to mid-1980s and early 1990s. This cooling is thought by some to have played an important role in the dramatic decline of Atlantic cod and other demersal fish and the increase in crustaceans, especially northern shrimp. The decline in water temperature was associated with an intensification of the Icelandic Low. An expression of this low that has commonly been used to correlate with physical and biological charateristics of the ecosystem is the sea-level air pressure difference between the Icelandic Low and the Bermuda-Azores High (the North Atlantic Oscillation or NAO). Off southern Labrador and northeastern Newfoundland, there is a well documented link between the positive phase of the NAO and intensified northwesterly winds, lower air temperatures, lower water temperatures and more extensive ice cover (Colbourne et al. 1994; Mann and Drinkwater 1994; Narayanan et al. 1995).

Fisheries and catches

A brief account of fisheries, catches, stock status and the influence of climate variability on biology is provided for each of the major species of fish or crustacean. Note that only species that are important in several ACIA areas, or are particularly important in a specific ACIA area (such as snow crab in the Labrador/Newfoundland area), are included in the study report. Therefore, this section is far from exhaustive, and several relatively important species, such as American plaice, are not included. Note as well that Atlantic salmon (*Salmo salar*) and marine mammals are to be discussed in other chapters of the ACIA report. Catches are taken from official NAFO statistics (as of 7 January 2002) or from relevant assessment documents if there is a difference between the two (see, for example, Anon. 2001b,c).

Atlantic cod (*Gadus morhua*) (Fig. 1)

The distribution of Atlantic cod along the coast of Canada has historically been from the northern Labrador Shelf southward beyond the limit of this study, although during the 1990s there have been few cod off Labrador. The Atlantic cod tends to live on the continental shelf, but it has been found at depths to at least 850 m on the upper slope off eastern Newfoundland (Baird et al. 1992).

The European fishery for Atlantic cod off eastern Newfoundland began in the late 15th century. For the first few centuries fishing was by hook and line, so the cod were exploited only from late spring to early autumn and only in shallow water along the coast and on the plateau of Grand Bank to the southeast of the island. There is evidence that local inshore overexploitation was occurring even in the 19th century (Cadigan 1999), but improvements in gear (linetrawls, cod seines and cod traps) and expansion of the area fished tended to compensate for local reductions in catch per effort. The deep waters, both inshore and offshore, remained refugia until the 1950s, when longliners designed to exploit populations of cod in deep coastal waters were introduced to eastern Newfoundland and distant water fleets from Europe started to employ bottom-trawlers to fish the deeper water of the outer banks, first mainly in summer/autumn but later in the winter and early spring when the cod were highly aggregated. Landings increased dramatically in the 1960s as large numbers of bottom-trawlers targeted the overwintering aggregations on the edge of the Labrador Shelf and the Northeast Newfoundland Shelf. At the same time, the numbers of large cod in deep water near the coast of Newfoundland are thought to have declined quickly as the longliner fleet switched to synthetic gillnets. Catches in SA 2 + Div. 3KL peaked at 894,000 t in 1968, and then declined steadily to only 143,000 t in 1978. Following Canada's extension of fisheries jurisdiction to 200 nautical miles in 1977, the stock recovered somewhat and catches were in the range 230-270,000 t during most of the 1980s. However, catches fell rapidly during the early 1990s as the stock declined to very low levels, and a moratorium on fishing was declared in 1992. A small fishery, limited to the inshore, was reintroduced in 1998. Additional details on the history of the Atlantic cod fishery of Newfoundland and Labrador, including changes in technology and temporal variability in the spatial distribution of fishing effort, may be found in Templeman (1966), Lear and Parsons (1993), Hutchings and Myers (1995), Neis et al. (1999), Hutchings and Ferguson (2000) and many others.

As with most heavily fished stocks, it is difficult to distinguish the influence of climate variability from the influences of intensive fishing and interactions with other species, both predators and prey. For the cod off Labrador and eastern Newfoundland, the fishery was clearly the major factor in the decline during the latter half of the 20th century. For the ultimate collapse, there is controversy as to whether there was a rapid but progressive decline from the mid-1980s onward or a precipitous decline during the early 1990s (Atkinson and Bennett 1994; Shelton and Lilly 2000). The former would imply that the estimates from research vessel surveys were severely positively biased for several years. The latter would imply that a very large quantity of fish unaccountably disappeared, either from greatly increased natural mortality or from greatly increased unrecorded fishing mortality (including perhaps both under-reported catches and non-reported discards). Many studies (e.g. Hutchings and Myers 1994; Myers and Cadigan 1995; Hutchings 1996; Myers et al. 1996 a,b, 1997 a,b; Haedrich et al. 1997) have concluded that the collapse was caused entirely by fishing activity (landed catch plus discards). However, several authors point to various ways in which the decline in water temperature might have contributed to the collapse, either directly by reducing productivity (Mann and Drinkwater 1994; Drinkwater 2000, 2002a; Parsons and Lear 2001) or indirectly by affecting distribution (Rose et al. 2000). See also Rice (2002) for an overview.

The severe decline of Atlantic cod in the Newfoundland-Labrador area seems to have occurred from north to south. On the northern and central Labrador shelf (Div. 2GH) catches of 60-90,000 t were reported in the period 1965-1969, but catches declined to less than 5,000 t in most years during the 1970s and early 1980s, to less than 1,000 t during the latter half of the 1980s and to zero in 1991. There appear to be no analyses of factors that contributed to the decline in this northern area. In the area from southern Labrador to the northern Grand Bank (Div. 2J+3KL), catches declined during the 1970s, improved during the 1980s, and then declined precipitously in the late 1980s and early 1990s. The period of the collapse was accompanied by a dramatic change in distribution of Atlantic cod in Div. 2J, 3K and northern 3L. The autumn research vessel surveys, winter acoustic surveys and the distribution of the winter/spring trawler fleet all indicating that the fish disappeared first from the north and west, became increasingly aggregated near the shelf break in the south and east, and finally disappeared almost completely by 1994 (Baird et al. 1992; Lilly 1994; Kulka et al. 1995; Wroblewski et al. 1995; Rose and Kulka 1999). There has been controversy regarding whether this change in distribution pattern resulted from a southward shift in distribution or a pattern of fish dying out in a sequence from north to south. Various analyses have been presented in support of the hypothesis that at least some of the cod shifted southward, possibly in response to a decline in water temperature (deYoung and Rose 1993; Rose et al. 1994; Atkinson et al. 1997; Rose et al. 2000) or a southward shift in the distribution of capelin (Rose et al. 2000). Indeed, Rose et al. (1994) indicated that this final shift in the late 1980s and early 1990s was part of a pattern of north/south displacements of several degrees of latitude in response to warming and cooling of water temperature. Other analyses found no support for the southward shift hypothesis (Hutchings and Myers 1994; Hutchings 1996; Myers et al. 1996a). It is important to know whether a southward shift actually occurred, because it is postulated that such a shift made the cod more accessible to fisheries as the stock declined (Rose and Kulka 1999; Rose et al. 2000), and because the more southerly distribution placed the cod in a position that is hypothesized to be disadvantageous for successful reproduction (deYoung and Rose 1993; Rose et al. 1994; Rose et al. 2000).

Temperature and other oceanographic factors have been shown or hypothesized to have influenced various elements of productivity (recruitment, individual growth and mortality) in the Atlantic cod off southern Labrador and eastern Newfoundland. Recruitment may be affected by the magnitude of the spawning stock and two easily measured oceanographic variables, temperature and salinity. Numerous studies have demonstrated a positive association between spawning stock biomass and recruitment (e.g. Rice and Evans 1988; Myers et al. 1993; Hutchings and Myers 1994; Morgan et al. 2000). However, Drinkwater (2002a) pointed out that both spawning stock biomass and recruitment experienced a long-term decline from the 1960s to the late 1980s, and that a statistical demonstration of the influence of spawning biomass on recruitment does not hold if the data are first-differenced to remove trends. With respect to environmental influences, there is expectation that recruitment in 2J+3KL cod might be positively influenced by warm temperatures, because the stock is at the northern limit of the species' range in North America (Planque and Frédou 1999), but there have been conflicting reports of whether such a relationship can be detected (deYoung and Rose 1993; Hutchings and Myers 1994; Taggart et al. 1994; Planque and Frédou 1999). Similarly, a reported relationship between recruitment and salinity (Sutcliffe et al. 1983) was subsequently supported (Myers et al. 1993) and later rejected (Hutchings and Myers 1994; Shelton and Atkinson 1994) as data for additional years became available. With respect to individual growth, a negative impact of temperature has been well documented (Krohn et al. 1997; Shelton et al. 1999). With respect to mortality, the possible influence of cold water is of considerable interest because of an apparent coincidence between the rapid disappearance of cod from research surveys and the low temperature and extensive ice cover of the early 1990s. While it seems unlikely that significant numbers of fish died as a direct consequence of exposure to cold water, there is still insufficient evidence to reject the possibility that the cold water and extensive ice cover led to a reduced duration of feeding opportunity, which itself led to poor body condition and death (Dutil and Lambert 2000; Lilly 2001).

The question of whether there was an increase in natural mortality in the 1980s and early 1990s, and whether any such increase was related to environmental factors, is of great importance to understanding the dynamics of Atlantic cod and other demersal fish (Lilly 2002; Rice 2002). As noted above, it is difficult to account for all the Atlantic cod that disappeared from the system without invoking either a considerable increase in non-reported fishing mortality or an increase in natural mortality. A similar controversy surrounds the American plaice stock off Labrador and northeastern Newfoundland (SA 2 + Div. 3K), which declined to a very low level through the 1980s and early 1990s, a period during which reported catches were low (Bowering et al. 1997). Hutchings (1996) presented a scenario illustrating how substantial quantities of American plaice may have been caught and discarded in the Atlantic cod fishery, but Morgan et al. (2002) re-examined his analyses and concluded that fishing was not the cause of the decline. Most other species of demersal fish, including many of no commercial value, declined dramatically through the same period. It has been stated that fishing was the cause of all these declines (Haedrich and Fischer 1996; Haedrich and Barnes 1997; Haedrich et al. 1997). However, the available data consist of indices of stock abundance and estimates of removals by the fishery, with little or no information on discards and incidental fishing mortality, so it is not possible to ascertain either the number of fish initially in the water or the number killed by the fishery. Under such circumstances, it remains somewhat a matter of faith to ascribe the declines entirely to fishing and to reject the possibility that natural mortality increased.

The Div. 2J+3KL cod stock remained at a very low level one decade after declaration of the moratorium (Lilly et al. 2001; DFO 2002a). Recruitment to ages 0-2 remained very low, possibly due in part to a very small spawning biomass, juveniles in the offshore appeared to experience very high mortality, possibly due in part to predation by harp and hooded seals, and a directed fishery reopened in 1998 on the small aggregations in the inshore, resulting in increased mortality on the larger fish. In the presence of unquantified impacts of low spawning stock biomass, high predation and commercial fishing, it is difficult to ascertain whether some aspect of ocean climate had a role in impeding recovery.

Greenland halibut (*Reinhardtius hippoglossoides*) (Fig. 2)

The Greenland halibut is distributed off West Greenland from Cape Farewell northward to about 78º N and thence southward off eastern Canada to beyond the limit of this study. It is a deep-water species, occuring in depths from about 200m to at least 2200 m off West Greenland (Bowering and Brodie 1995).

The history of the fishery is complicated by temporal and spatial variation in effort and catch by different fleets and by alleged underreporting of landings. For details of the fisheries, refer to Bowering and Brodie (1995), Bowering and Nedreaas (2000) and Anon. (2001c).

The fishery off eastern Newfoundland dates back to the mid-19th century (Bowering and Brodie 1995; Bowering and Nedreaas 2000). Catches from longlines were less than 1000 t annually until the early 1960s, when catches began to increase substantially. With the introduction of synthetic gillnets in the mid-1960s, catches in inshore waters rose quickly but declined within a few years, after which the fishery spread onto the shelf. Landings from offshore trawlers, mainly from European countries, also increased after the mid-1960s. Catches in SA 2 + Div. 3KL fluctuated near 25-35,000 t from the late 1960s to the early 1980s, after which there was a gradual decline to about 15,000 t in 1986. Landings increased dramatically in 1990 with the arrival of many non-Canadian trawlers that fished deep waters of the Sackville Spur and Flemish Pass. Catches during the next four years were high (estimated at 55-75,000 t in 1991 (Anon. 2001c)), declined substantially in 1995 due to an international dispute, and increased again during the late 1990s under NAFO quotas that maintained catches well below those estimated for the early 1990s.

The fishery to the north (SA 0), which has been conducted primarily with otter trawlers in the second half of the year (Bowering and Brodie 1995), reported an average of 2,100 t during 1968-1989 (including a high of 10,000 t in 1972). Catches increased dramatically to 14,500 t in 1990 with increased effort by Canada, but declined to about 4,000 t from 1994 onward. These landings came mainly from off southeastern Baffin Island (Div. 0B). The fishery expanded even further north into Baffin Bay (Div. 0A) in the mid- to late 1990s (Treble and Bowering 2002). This fishery, which extended to 73^{o} N in 2002 (M.A. Treble, DFO, Central and Arctic Region, pers. comm.), has been limited by ice cover to the months of September to November.

The status of Greenland halibut in the northwest Atlantic has been uncertain because stock structure remains unclear, the fish undertake extensive ontogenetic migrations, there appear to have been shifts in distribution, the fisheries have undergone numerous changes in fleet composition and areas and depths fished, and individual research surveys have been able to cover only part of the very large area and depth range occupied by the fish. Nevertheless, there is evidence from various surveys that the biomass of Greenland halibut on the western side of the Labrador Sea declined substantially during the 1980s, with the decline in Div. 0B and 2GH being most pronounced during the first half of the decade and the decline in Div. 2J3K to the south being most pronounced during the second half of the 1980s and the early 1990s (Bowering and Brodie 1995). Evidence for a decline in biomass in Div. 2J3K is also seen in declining success of the gillnet fishery during the 1980s. The history of the fish exploited during the 1990s by the new deep-water trawler fishery to the south in Flemish Pass is less clear. It is possible that at least some of these fish migrated into the area from the shelf to the north (Bowering and Brodie 1995), in which case the decline in Div. 2J3K was partly due to a southward shift in distribution.

The reason for the declines in biomass and shift in distribution remains unclear. Bowering and Brodie (1995) drew attention to the decline in water temperatures on the shelf that occurred during the early 1990s, but thought that it was unlikely that such a change would in itself have affected the distribution and abundance of Greenland halibut because this species occupies relatively deep water. It may also be noted that much of the shift in distribution must have occurred during the latter half of the 1980s, a period during which water temperatures were low but not as low as during the early 1990s.

Other than the change in distribution noted above, variability in the physical environment has had no observed effect on the biology of Greenland halibut in the Labrador-Newfoundland area. In contrast to the dramatic changes observed in Atlantic cod, there has been no discernable trend in either size at age (Bowering and Nedreaas 2001) or maturity at size or age (Morgan and Bowering 1997) during the period from the late 1970s to the mid-1990s.

The influence of biological interactions on the distribution and abundance of Greenland halibut in the Labrador-Newfoundland area has received little attention.

Capelin (*Mallotus villosus*) (Fig. 3)

Prior to the initiation of a commercial offshore fishery during the early 1970s, capelin were fished on or near the spawning beaches. Annual catches, used for local consumption, may have reached 20,000 to 25,000 tons (Templeman 1968). Offshore catches by foreign fleets increased rapidly, peaking in 1976 at about 370,000 tons, and then declined rapidly. This offshore fishery continued at a low level until 1992. Catches in the offshore fishery were taken at different times of the year in different areas. The spring fishery was dominated by USSR midwater trawlers operating in Div. 3L. During the autumn, the offshore fishery first occurred in Div. 2J, off the coast of Labarador, and gradually moved south into Div. 3K as the capelin migrated towards their overwintering area. This fishery was dominated by USSR midwater trawlers, which took mostly feeding and maturing capelin that would spawn the following year. During the late 1970s, as the foreign fishery declined, Canadian fishermen began fishing mature capelin near the spawning beaches to supply the Japanese market for roe-bearing females. This fishery expanded rapidly, exhibited highest catches during the 1980s and declined during the 1990s. The catches in the inshore fishery have generally not been as high as those from the offshore foreign fishery.

Although the fishery on Canadian capelin has been relatively small when compared to the capelin fisheries in Iceland and the Barents Sea, there has been a concern about the potential impact of a commercial fishery on capelin because of its role as a forage species. However, Carscadden et al. (2001) concluded there is no scientific evidence to support the notion that the fishery in SA2+Div. 3KL has had an impact on population abundance.

The relationships between capelin biology and the physical environment have been extensively studied in the Newfoundland and Labrador area. Capelin biology changed during the 1990s and significant relationships between some changes (spawning time, distribution) and the environment have been reported. For the most part, these studies examined data from the 1980s and early 1990s. The latter part of this period was characterized by unusually low water temperatures coincident with the changes in capelin biology. Water temperatures during the latter half of the 1990s have ameliorated, yet the biological changes of capelin (including those which had been statistically linked) have not reverted to the patterns observed during earlier periods.

There has not been a formal analysis of capelin growth in the area, however, the mean fish length of the mature population has been smaller during the 1990s. These small sizes have been attributed to smaller fish sizes at age and fewer older and more younger fish in the population. During the 1990s, there has been less growth between autumn and spring than during the 1980s. This change first occurred during the time when water temperatures were below average (Carscadden et al. 1999). However, this pattern persisted at least until autumn 1999/ spring 2000, when water temperatures had returned to normal.

Spawning appears to be substrate specific, occurring most often on fine gravel ranging from 0.1 mm to 16.6 mm in diameter (Vilhjalmsson 1994; Nakashima and Taggart 2002). Nakashima and Taggart (2002) showed that beach orientation and grain size explained 61% of the variation in egg concentration among beaches.

Water temperature has also been cited as a determinant of capelin spawning and while ranges of spawning temperatures have been reported, preferred temperatures have not been clearly identified. The recorded lowest and highest temperatures for beach spawning in Newfoundland are 3.5 and 11.9^{o} C, with beach spawning ceasing when temperatures exceeded 12.0^{o} C (Nakashima and Wheeler 2002).

Capelin eggs are very cold- and salinity-tolerant. Eggs laid by intertidal spawners in Balsfjord, Norway survived temperatures as low as –5^{o} C and thrived in salinities ranging from 3.4 ‰ to 34 ‰ (Davenport and Stene 1986). The results for eggs from bottom spawners in Iceland were similar (Davenport 1989). The rate of egg development in the beach gravel is directly related to average incubation temperatures which in turn are determined by water temperature, maximum and minimum air temperature and hours of sunlight (Frank and Leggett 1981).

Some capelin that move close to beaches to spawn eventually spawn in deeper water adjacent to beaches. This demersal spawning can occur simultaneously with intertidal spawning when temperatures are suitable as well as when water temperatures at the beach-water interface become too warm. Egg mortality among these demersal eggs has been observed to be higher. Reproductive success may have been poorer during the 1990s because water temperatures encountered when the capelin reached the spawning beaches would have increased the incidence of demersal spawning (Nakashima and Wheeler 2002).

Historically, the spawning of capelin off Newfoundland beaches during June and July was a well-known and highly predictable event. During the early 1990s, spawning was later, and Carscadden et al. (1997) reported that 80% of the variation in spawning time (1978-1994) was significantly and negatively related to mean fish size and sea temperatures that capelin experienced during gonadal maturation. Capelin spawning on Newfoundland beaches has continued to be delayed through 2000 in spite of the fact that sea temperatures have returned to normal. However, mean lengths of capelin have continued to be small throughout this period .

Historically, capelin have been reported outside their normal distribution range. Unusual appearances in the Bay of Fundy during 1903, 1915-1919 and 1965-1968, and on the Flemish Cap in 1973 were attributed to cooler water temperatures while occurrences in Ungava Bay during 1884 and 1959 coincided with warming trends (summarized in Frank et al. 1996).

During the early 1990s, capelin essentially disappeared from Div. 2J adjacent to the Labrador coast, to occupy an area to the south on the northern Grand Banks. Originally attributed to the colder water temperatures during the early 1990s (Frank et al. 1996), this shift within the normal distribution area has continued through 2000. Outside their normal distribution area, capelin occurred on the Flemish Cap and eastern Scotian Shelf during the early 1990s and occasionally during earlier cold periods. They were not found there during every cold period, suggesting that cold sea temperatures were a necessary but not a sufficient condition for capelin to occur outside their normal range (Frank et al. 1996). Capelin continued to appear on the Flemish Cap in small numbers through 2000 and in large numbers on the eastern Scotian Shelf through 2000. In the latter area, sea temperatures were beginning to warm during the late 1990s, but they were still below the long-term mean (Drinkwater et al. 1999).

It appears that in the case of the large-scale changes in distribution outside their normal area, capelin are gradually declining in abundance as the waters warm. However, within their normal area of distribution, capelin have not returned to their usual pattern of seasonal distribution as water temperatures increased, suggesting that other factors may be operating.

For mature capelin on the Grand Banks during spring, 1980s and early 1990s, distribution was not associated with temperature on relatively small (~2000 km^2) spatial and temporal (within year) scales, but was on larger spatial (~90,000km^2) and temporal (among years) scales. It was concluded that temperature was not used as a proximate cue during migration but that seasonal temperatures moderated offshore capelin migration patterns through the regulation of growth, maturation, food abundance and distribution (Shackell et al. 1994).

Capelin typically move up and disperse in the water column at night and descend and aggregate at greater depths during the day, but during spring surveys throughout the 1990s they remained deeper in the water column and exhibited reduced vertical migration (Shackell et al. 1994; Mowbray 2002). This alteration in vertical distribution was not related to temperature, fish size or maturity stage but was significantly related to capelin density and proximity of cod, a major predator. Euphausiids, a key food item during the 1980s, were less frequent in stomachs during 1999 and 2000 and this may explain the deeper occurrence of capelin (Mowbray 2002).

Condition of capelin was generally higher during the 1980s than during the 1990s. Condition was not related to temperature (Carscadden and Frank 2002). Zooplankton data were not adequate to test the relationship between condition and zooplankton but the observations of fewer euphausiids in capelin stomachs (Mowbray 2002) suggests that food abundance may be influencing condition.

Two studies have demonstrated positive relationships between recruitment and the environment. The first established that the frequency of onshore winds during larval residence in the beach gravel and surface water temperatures six months after exit from the beach gravel explained about 58 % of recruitment variation (Leggett et al. 1984). In a later test of the model using a longer time-series (which did not include the 1990s), Carscadden et al. (2000) reported that the temperature component of the model was no longer significant but the onshore wind component was still significant, explaining 25 % of the variation of pre-recruit survival.

The assessment of capelin has been especially problematic since the early 1990s, making the stock status highly uncertain. Abundance indices developed to measure relative capelin abundance have shown different trends. All exhibit annual variations, however, offshore acoustic densities have been low since 1990 while inshore indices have not declined to the extent expected from the offshore indices. Even if the number of individuals in the population were unchanged during the 1990s (and this is unknown), the smaller mean sizes would imply an overall decline in biomass. It is not known whether some changes in biology such as condition and distribution have affected abundance, however, spawning time and increased demersal spawning may be contributing to poor survival .

Herring (*Clupea harengus*)

Herring in the Newfoundland and Labrador area are at the northern extent of their geographic range. Stocks are coastal in distribution and stock abundance is small compared to other stocks in the Atlantic. Recruitment is positively related to warm overwintering water temperatures and high salinities (Winters and Wheeler 1987); these conditions seldom exist in this region and as a result, large yearclasses rarely occur. A peak catch of 30,000 t occurred in 1979, supported by strong yearclasses from the 1960s. Recruitment since the 1960s has been lower. Stock sizes during the late 1990s have been less than 90,000 t and annual catches have been less than 10,000 t (DFO 2000a).

Arctic (polar) cod (*Boreogadus saida*)

The Arctic cod is broadly distributed through the Arctic and in cold waters of adjacent seas. It occurs on the shelf from northern Labrador to eastern Newfoundland, with the average size of individuals and the size of aggregations decreasing from north to south (Lear 1979). During the cold period of the early 1990s the distribution of Arctic cod off eastern Newfoundland expanded to the south and east (Lilly et al. 1994; Lilly and Simpson 2000). There has been no directed fishery for Arctic cod off eastern Canada, but a small bycatch was reported in the Romanian capelin fishery in 1979 (Maxim 1980), and it is likely that small quantities were also taken in other years and by other countries .

Northern shrimp (*Pandalus borealis*) (Fig. 4)

The northern shrimp is distributed off West Greenland from Cape Farewell northward to about 74º N and thence southward off eastern Canada to beyond the limit of this study. The depth of highest concentration tends to vary from area to area but is generally in the range 200-600m.

A fishery with large trawlers began off northeastern Canada in the late 1970s (Orr et al. 2001a). For the first decade most of the catch was taken from two channels in the central and southern Labrador Shelf, but in the late 1980s there was an increase in effort and landings both to the south on the Northeast Newfoundland Shelf and to the north off northern Labrador. Catches increased above 25,000 t by the mid-1990s. When the science survey trawl was changed to a shrimp trawl in 1995, it became apparent that commercial catches of shrimp were very small relative to survey biomass, and quotas were increased considerably during the late 1990s. Total landings from the area rose to more than 90,000 t by 2000. Much of the increase in catch from 1997 onward came from a new fleet of small (< 100 feet) vessels that fished bottom trawls primarily on the mid-shelf. During the 1990s fishing also expanded to Div. 3L in the south (Orr et al. 2001b).

The shrimp resource off northeastern Canada has increased in density and expanded in distribution since the mid-1980s. There is no indication that the increase in catch has negatively impacted the resource (DFO 2002c).

There is considerable support for the hypothesis that the increase in northern shrimp off northeastern Canada was, at least in part, a consequence of a reduction in predation pressure by Atlantic cod and other groundfish (Lilly et al. 2000; Bundy 2001; Worm and Myers 2002). Nevertheless, there is evidence that other factors were involved. For example, Lilly et al. (2000) noted that the increase in shrimp density on the Northeastern Newfoundland Shelf might have started during the early 1980s, a time during which the biomass of Atlantic cod was increasing toward a peak in the mid-1980s following its decline during the 1970s. Parsons and Colbourne (2000) found that catch per unit effort in the shrimp fishery on the central Labrador Shelf was positively correlated with ice coverage 6 years earlier. They suggested that cold water or ice cover itself was beneficial to the early life history stages of shrimp in that area.

Snow crab (*Chionoecetes opilio*) (Fig. 5)

The snow crab is distributed from the central Labrador Shelf at approximately 55º N southward off eastern Canada to beyond the limit of this study. The depth distribution extends from approximately 50 m to 1400 m, but most of the fishery occurs in 100-500 m.

The fishery off eastern Newfoundland began in the late 1960s as a bycatch from gillnets set for demersal fish within one bay, but soon expanded into a directed fishery with crab traps (pots) along most of the inshore areas of the east coast (Div. 3KL) (Taylor and O'Keefe 1999). During the late 1970s and early 1980s there was an increase in effort and an expansion of fishing grounds. Catches in Div. 3KL reached almost 14,000 t in 1981, but then declined. In the mid-1980s there was expansion of the fishery into Div. 2J and new entrants gained access to supplement declining incomes from the groundfish fisheries. The number of participants and the area fished expanded further during the 1990s, and total 2J3KL catches rose quickly, reaching almost 55,000 t in 1999. Quotas and landings were reduced for the subsequent two years under concerns that the resource may have declined.

Commercial catch rates in Div. 3KL increased during the late 1970s to a peak in about 1981, declined to a nadir by 1987, and then increased during the late 1980s and early 1990s to a level comparable to that in the early 1980s (DFO 2002b). Catch rates remained high to the end of the 1990s, despite the substantial increase in fishing effort and landings. This reflects in part an increase in the area fished, but it is thought that there must also have been an increase in productivity. Fishery-independent indices of biomass over the whole area became available upon introduction of the Campelen trawl to the research vessel surveys in autumn 1995. A comparison between catches and an exploitable biomass index calculated from survey catches suggests an increase in exploitation rate during the late 1990s (DFO 2002b).

The increased productivity of snow crab during the 1990s may have been caused, at least in part, by the release in predation pressure from Atlantic cod and other demersal fish (Bundy 2001). However, the relationships between Atlantic cod and snow crab have not yet been explored to the extent that they have for Atlantic cod and northern shrimp. A preliminary examination of the influence of oceanographic conditions upon productivity of snow crab has revealed a negative relationship between ocean temperature and lagged catch rates (DFO, 2002b). This has been interpretated to indicate that cold conditions early in the life cycle are associated with the production of strong year-classes of snow crab in this area.

Possible impact of climate change

Predicted global warming due to increased CO_2 emissions has been a major concern in recent years, resulting in a number of scientific studies which address the consequences to ecosystem dynamics. As examples, we describe two that are of particular relevance to possible impacts of fisheries occurring in this ACIA region. The most recent (Shuter et al. 1999) is part of a larger study that addressed the issue of climate change throughout Canada. Although the geographical scope of the study pertaining to the fisheries sector is much larger than this portion of the ACIA study, there are several relevant conclusions. The Cross Canada Study concluded that greenhouse gas accumulation will lead to a warmer, drier climate and for Atlantic regional fisheries, this will result in a " decrease in overall sustainable harvests for coastal and estuarine populations due to decreases in freshwater discharge and consequent declines in ecosystem productivity; widespread changes in sustainable harvests, locations of fishing grounds and gear efficiencies for many populations due to complex and likely unpredictable changes in the ocean current systems that shape offshore marine habitats". In the Northwest Atlantic, the authors speculate that overall production in the ecosystem will probably decline because of the change in wind-driven turbulence and the negative effect on phytoplankton. Specifically, overall production in the area has been related to the NAO. A positive NAO results in cold winters, strong northwest winds in winter and spring, extensive and prolonged ice cover and after ice melt, fresher surface waters. These periods with positive NAO and the associated physical attributes have been shown to result in shorter growing seasons for phytoplankton and zooplankton, which contributes to reductions in population biomass of groundfish, reductions in biomass of some pelagic species and reductions in growth and population biomass of cod (Shuter et al. 1999). Shuter et al. (1999) also noted that the spatial distribution of many species might change with climate change and this change may be rapid for marine species because there are essentially no physical barriers. As an example of a distributional change due to environmental change, they cite the movement of capelin to the south during the cooling period of the 1990s. While change in distribution may be illustrative of such a phenomenon and the fish behaved as might be expected, it is interesting that there was a general cooling in the area rather than a warming, which might have been expected under a global warming scenario.

This example and the examples described in the second paper (Frank et al. 1990) serve to illustrate the uncertainties involved in predicting the future state of ecosystems and the fisheries. Frank et al. (1990) predicted the response of various stocks of fish and invertebrates to climate change that might occur as a consequence of CO_2-induced climate change. They noted that their analysis was "highly speculative, in part because of uncertainties in the predicted physical changes, but also because of the limited knowledge of the processes linking physical oceanography with fisheries". Building on the predictions of others, including an anticipated general warming and freshening of continental shelf waters, they predicted shifts in the geographic ranges of several groundfish stocks because of redistribution of populations and changing recruitment patterns. Stocks at the southern limit of a species' distribution should retract northward, whereas those near the northern limit should expand northward. Frank et al. (1990) did not make predictions specifically for Labrador and eastern Newfoundland, but the above generality should apply. Such predictions regarding geographic shifts may ultimately prove correct, but events off northeastern Canada during the decade following publication of the paper were in many respects opposite to that predicted. Most species of demersal fish did not expand distributions northward on the Labrador Shelf, but rather experienced severe declines and in many cases experienced a southward shift in distribution (Atkinson 1994; Gomes et al. 1995). Within the pelagic community capelin, an arcto-boreal species, became less abundant off Labrador and Arctic cod, an arctic species, experienced an expansion southward. This failure of the predictions, at least in the short term, was not necessarily a failure to correctly predict biological responses to oceanographic changes. During the period of global warming during the last 2-3 decades of the 20th century, the waters off Labrador and eastern Newfoundland experienced a cooling trend, with particularly cold periods in the early 1970s, early to mid-1980s, and early 1990s. Thus, to the extent that the biological changes are a response to physical changes, as opposed to a response to overfishing, the failure of the predictions in the short term may be viewed as a consequence of a regional deviation from the generality of a warming of shelf waters.

Changes in the biological components of the ecosystem off northeastern Canada have been variously ascribed to overfishing, climate variability, changes in predation pressures or a combination of these factors. The relative importance of fishing and environment is difficult to determine for any species or group of species, so it is perhaps not surprising that the importance attributed to each has varied among studies. It is also perhaps not surprising, given the differences among species in the magnitude of fishery removals relative to stock size, that opinion tends to favour fishing as the dominant factor for some species and environment as the dominant factor for others. For demersal fish, there are many statements to the effect that declines were caused entirely by overfishing. Nevertheless, there is evidence that changes in oceanographic properties contributed to changes in distribution and declines in productivity (including decreased individual growth rate and possibly decreased recruitment and increased mortality). For crab and especially shrimp, it has been suggested that increases in biomass were simply a consequence of a release in predation pressure from Atlantic cod and perhaps other demersal fish, but again there is evidence that changes in oceanographic factors contributed to an increase in reproductive success. For capelin, most information supports the hypothesis that fishing had little impact on population dynamics, and that environmental factors were the primary determinant of stock size, well-being (growth and condition), distribution and timing of migrations. For Arctic cod, fishing may be dismissed as a contributor to changes in distribution and biomass.

Accurately predicting the response of the ecosystem to oceanographic changes that might accompany climate warming is exceedingly difficult, not only because we have not clearly elucidated the influence of oceanographic variability in the past, but also because it is possible that the dynamics of some species are now dominated by a different suite of factors than was the case in the past. It is highly likely that the ecosystem changed substantially as a consequence of fishing during the first four centuries following the arrival of fishermen from Europe, changed even further with the increasingly intensive fishing of the 20th century, and altered very dramatically during the last two decades of the century. It would be difficult to predict accurately the future state of the system, even without the added complications of climate change. The system could remain in its current state, revert to some semblance of an historic state (or at least the state of the early 1980s), or evolve toward something previously unseen. It is notable, however, that there has been no recovery of Atlantic cod despite a moratorium for a series of years (mid-1992 - 1997) and only a small fishery limited to inshore waters during 1998-2002. In addition, changes that occurred in capelin biology during the cold period of the early 1990s have not substantially reversed during the warmer years that followed the mid-1990s.

We have been charged with predicting changes in fish stocks and the fisheries that exploit them in the northeastern Canadian area over periods extending to 2020, 2050 and 2080. Physical oceanographic variables that may influence the distribution and productivity of fish stocks include water temperature and salinity throughout the water column, ice extent and duration, vertical stratification, current strength and sea level. Unfortunately, global climate models now in use generally do not provide projections for these oceanographic variables. In fact, the only relevant variable available is surface air temperature, and for this assessment we have assumed that changes in sea surface temperatures will be of approximately the same magnitude as surface air temperatures. Furthermore, because of the spatial resolution of the global climate models, the predictions of basic climatic variables, such as air temperatures, are considered unreliable at the regional level (Anderson et al. 1999), thereby adding further uncertainty to predictions of changes in regional fish stocks and fisheries.

It is imperative that region-specific projections be available for future assessments, because even the direction of change of a fundamental variable such as water temperature may differ among regions and over time. Some areas may experience cooling while the global mean temperature rises. For example, some model outputs predict a cooling of surface air temperature over the central North Atlantic, and it is not at all clear where the Labrador/Newfoundland region lies within the gradation from significant warming in the high Arctic to cooling over the central North Atlantic. Although many large-scale models predict an increase in air temperature over the Norwegian and Barents seas, simulations with one specific model indicate that sea surface temperature in that area may decline in the next 20 years before increasing later in the century (Furevik et al. 2002). Another concern with predictions of the physical environment is that natural variability in a specific region, such as the Labrador Shelf, may be much greater than variability in the global mean (Furevik et al. 2002). Thus, a warming trend in shelf waters off Labrador and Newfoundland might be accompanied by substantial annual variability, such as was witnessed during the last three decades of the 20th century, and it is even possible that the amplitude of that variability could increase. For biota, extreme events associated with this variability might be at least as influential as any long-term trend. For the Labrador Shelf and Northeast Newfoundland Shelf, it is probably at least as important to know how the NAO will behave (especially the intensity and location of the Icelandic Low) as it is to know that global temperature will rise.

In the absence of region-specific information, we have assumed that there will be a gradual warming of shelf waters off Labrador and Newfoundland. Using the events in West Greenland during the first half of the 20th century (Vilhjálmsson 1997) as a spatial/temporal analogue, one might expect better recruitment success and northward expansion of Atlantic cod and some other demersal fish that live mainly on the shelf. However, the manner in which climate variability in the past has influenced distribution and productivity of Atlantic cod off Labrador and northeastern Newfoundland remains controversial, so predictions will probably remain vague. Capelin also would be expected to shift northwards. If zooplankton abundance is enhanced by warmer water, capelin growth may well improve. The yearclass strength of capelin (recruitment) appears to be largely determined early in their life history. Therefore, sea level rise and its effect on the beach environment, time of spawning and extent of demersal spawning, as well as the complex of environmental conditions occurring on the beach during egg development, could interact in a complex manner to determine recruitment. The complexity of these factors coupled with a general lack of knowledge of how they interact makes the accurate prediction of future capelin recruitment under global climate change scenarios impossible. It is also possible that many existing capelin spawning beaches will disappear with the predicted rise in sea level. Recent studies (Shaw et al. 1998) indicate that the effect of sea level rise on Canadian coastal environments is likely to be highly variable. In Atlantic Canada, gravel beaches are considered more sensitive than, for example, cliffs, and it is these gravel beaches which are the preferred spawning locations for Newfoundland and Labrador capelin. Depending on the increase in sea level, storm events and the availability of glacial deposits, some beaches may move while others may disappear completely. While capelin appear to be able to adapt to spawning on suitable sediment in deeper water (Carscadden et al. 1989; Nakashima and Wheeler 2002), survival of eggs and larvae appears to be adversely affected (Nakashima and Wheeler 2002), suggesting that a rise in sea level would probably result in reduced survival and recruitment for capelin. A warming of sea temperatures might retard recruitment to snow crab and northern shrimp, so these species might experience gradual reductions in productivity. In summary, then, we might anticipate that a gradual warming of sea temperature might promote a change back to a cod-capelin system from the present system where snow crab and northern shrimp are the major commercial species, and both cod and capelin might become more prominent off central Labrador than they were during the 1980s.

The above simple scenario of a gradual change back to a cod-capelin system is very uncertain because of insufficient knowledge of how individual species will respond to oceanic warming. In addition, there is much uncertainty associated with the potential impacts of fishing, biological interactions and internal species dynamics. It is possible, for example, that on-going directed and by-catch fisheries could catch sufficient Atlantic cod and other demersal fish to prevent their recovery. In addition, fisheries might over-exploit snow crab or northern shrimp, thereby reducing their abundance and possibly triggering additional changes in the ecosystem. With respect to biological interactions, some authors (Swain and Sinclair 2000; Walters and Kitchell 2001) have suggested that when large, dominant fish species become severely depleted, they will not recover rapidly because forage species, which they formerly held in check (the "cultivation hypothesis"), will now become more abundant and cause increased mortality on their early life history stages . Although there is no indication that planktivorous fish have become more abundant, we should consider the possibility that snow crab larvae and northern shrimp may be having an important impact on the eggs and larvae of Atlantic cod and other demersal fish. Recovery of Atlantic cod and other demersal fish might also be retarded by predation from harp and hooded seals. With respect to internal dynamics, it is possible that some species, particularly snow crab, may decline for reasons that are independent of fishing pressure, interactions with other species and climate forcing.

A gradual warming of shelf waters might also promote a movement of more southerly species into the area. For example, haddock (*Melanogrammus aeglefinus*) might become more abundant on the southern part of Grand Bank, and expand into the study area. Migrants from the south, such as mackerel, short-finned squid and bluefin tuna, might occur more regularly and in greater quantities than during the 1980s and early 1990s.

In addition to uncertainty regarding the response of individual species and the ecosystem as a whole, there is uncertainty regarding the influence of changing ice cover on the fisheries themselves. A reduction in the extent and duration of sea ice may permit fishing further to the north and would increase the period during which ships would have access to certain fishing grounds. In particular, these changes in sea ice cover would affect the Greenland halibut and shrimp fisheries in Baffin Bay and Davis Strait. For example, an increased open water season and extended fishing period is thought to have the potential to increase harvest of Greenland halibut at the time of spawning (late winter/spring).

Conversely, a reduction in ice cover might negatively impact Greenland halibut fisheries that are conducted through fast ice. For example, a fishery that was started in Cumberland Sound on Baffin Island in the late 1980s has developed into a locally important enterprise (Crawford 1992; Pike 1994). The fishery is conducted with longlines set through ice over deep (600-1125 m) water, with the season extending in some years from mid-January to June. Since the mid 1990's, the season has been shorter, typically from early February to May (M.A. Treble, DFO, Central and Arctic Region, pers. comm.). To date, attempts at fishing during the open water season have not proved successful. The catches have been low and the fish seem to be dis-aggregated. It is not clear whether the fish would be present in commercial concentrations in the winter/spring if ice were not present. Even if they were, the absence of ice would certainly affect the conduct of the fishery.

Future Research

The ACIA assessment builds upon two kinds of scenarios. First, it assumes a moderate scenario for emissions (greenhouse gasses and aerosols). This is the IPCC SRES B2 scenario (IPCC 2001). It then uses climate scenarios, based on this emissions scenario, from five Atmosphere-Ocean General Circulation Models (GCM's). The climate scenarios have a baseline of 1980-1999 and projections to 2099, with particular attention directed to 20-year time slices centred on 2020, 2050 and 2080. Projections from the five models disagree on the magnitude of changes and regional aspects of those changes, but they all project that warming will be greater in the Arctic than elsewhere and that warming will be greater in winter than in summer.

The GCM output includes surface air temperature. However, there is no projection of many of the variables that may be important to commercially important species and their predators and prey. One may wish to know, for instance, current strength, temperature and salinity at various locations and depths; the position, intensity and duration of fronts; ice extent and duration; and derived variables such as stratification. **There is a need, then, for downscaling from GCM output to the physical oceanography of shelf waters off Labrador and Newfoundland**, such as has been done for the Nordic Seas by Furevik et al. (2002).

As noted above, there is considerable spatial variability in the projected change in surface air temperature, both within and among models. In one model, the temperature change projected for the 2080 time period varies from an increase of about 10^0 C off southeastern Baffin Island to a decrease of $2\text{-}3^0$ C in both the central Labrador Sea and to the southeast of Newfoundland. Such large projected changes in temperature over the range of a single species makes the accurate prediction of responses highly unlikely.

While Siberia and western North America experienced warming during the last three decades of the 20^{th} century, the area of northeastern Canada and West Greenland experienced a cooling, particularly during the period 1965-1995. That is, the baseline period for the GCM projections was relatively cool in the Labrador/Newfoundland area, and we wondered if temperatures comparable to those projected for the 21^{st} century had been experienced during the relatively warm period in the middle of the 20^{th} century. To explore this we compared projected surface air temperature (averaged from the output of three GCM models for the region of Baffin Bay and the Labrador Sea) to air temperatures recorded at Nuuk and St. John's during the 20^{th} and early 19^{th} centuries. An increase in air temperature comparable to that projected for the Baffin Bay/Labrador Sea area by about the mid-21^{st} century was seen in Nuuk during the late 1920s and 1930s. That warming led to extensions of cod, capelin and other species northward along the West Greenland coast and to a rejuvenation of the West Greenland cod fishery (Vilhjálmsson 1997; Buch et al. 2002). In contrast, air temperatures at St. John's in the 1920s and 1930s were not substantially greater than the average during 1980-1999. (It must be noted that use of the 1980-1999 period as a baseline is somewhat awkward for the Labrador/Newfoundland area because of the considerable variability experienced during that period. In particular, the early 1990s were very cold whereas the late 1990s were very warm.) In any event, it is the area north of St. John's that is perhaps of greatest interest here. We are most curious as to whether changes in the marine biota comparable to those seen at West Greenland in the middle of the 20^{th} century occurred off Labrador at about the same time. If they did not, then why? **There is a need for a search and synthesis of information on the marine biota of the Labrador Shelf and coast, going back at least to the latter part of the 19^{th} century. A similar search and synthesis, if not already available, is required for air and sea temperatures for the Cartwright – Hamilton Bank area.** (Note that surface air temperature records at Cartwright go back only to the mid-1930s.)

There are numerous examples of associations between some measure of environmental variability and some aspect of fish/crustacean biology or some aspect of a fishery (see, for example, Colbourne et al. (2002)). Correlation/regression analyses, of various degrees of sophistication, are important starting points for identifying such associations, but we need to move whenever possible toward understanding the mechanisms behind them. We also need to explore more thoroughly the residuals from such associations.

As is well understood, the past may not be a good key to the future, because circumstances change. This problem of non-stationarity may be looked at in a very literal way when one considers the influence of the North Atlantic Oscillation (NAO) on the environment and biota of the Labrador and Northeast Newfoundland Shelves. Many papers have drawn attention to the link between the positive phase of the NAO and intensified northwesterly winds, lower air temperatures, lower water temperatures and more extensive ice cover (e.g. Colbourne et al. 1994; Mann and Drinkwater 1994; Narayanan et al. 1995). However, there were years in the latter half of the 1990s when a strong positive NAO index did not lead to a cooling off Labrador and northeastern Newfoundland such as had been seen in the early 1970s, the early to mid-1980s, and the early 1990s. This was because the Icelandic Low had shifted somewhat to the east, and did not cause a flow of Arctic air over Labrador. There has been a tendency recently for many scientists to relate aspects of the physical and biotic environment to the NAO. **Perhaps it would help if a new climatological index could be developed for the Labrador Shelf area; one that incorporated both the strength of the Icelandic Low and its position relative to the shelf**. (On the other hand, perhaps the winds and air temperatures actually observed at Cartwright provide as much information as does an index such as the NAO.)

Physical oceanographers (e.g. Colbourne and Fitzpatrick 2002; Drinkwater and Petrie 2002) currently provide annual updates of numerous indices that provide metrics of monthly, seasonal or annual variability in various aspects of the environment. They also from time-to-time provide overviews of longer term variability, often in terms of decadal means (e.g. Colbourne 2002; Drinkwater 2002b). The indices are useful in that they provide information about the magnitude of changes in the environment and metrics that can be used to test hypotheses. However, the fisheries biologist also needs to develop a feeling for how each organism makes a living within that physical environment – how the life history characteristics of the species/stock are tuned to the mean state and variability of the environment. The fisheries biologist also needs to determine how the species/stock might respond to and be affected by changes outside the norm. The fisheries biologist would be aided in these tasks by **a primer that provides both a non-mathematical overview of the physical oceanography of shelf and slope waters off Labrador and eastern Newfoundland and a guide to the literature where technical details may be discovered**. Such a primer would assist the biologist in determining which of the currently available data sets and indices would be of relevance to any specific enquiry, and what additional data or indices would help to advance the enquiry.

Information that biologists might wish to find in such a primer include the following:

- A description, accompanied by 3-dimensional illustrations, of the average distribution of **water masses** in the Labrador Sea and adjacent shelf areas. This would include a discussion of the origin of these water masses.

- A 3-dimensional description of the mean **currents** in the area from Davis Strait to southern Newfoundland, including current positions and strengths. This would be accompanied by discussion of the causes and magnitude of variability in these currents at various temporal scales, from hours to decades.

- A description of the presence and strength of **gyres**, especially those around banks such as Belle Isle Bank and Funk Island Bank, and the existence of incursions of slope water onto the shelf, especially on the Northeast Newfoundland Shelf and southwestern Grand Bank.

- The **seasonal cycle** of warming and cooling, with a description of the downward progression of these processes at any given geographical point. (The sampling at Station 27 would presumably be the richest source of such information, but it would be helpful if there were also information from farther north, such as Hamilton Bank.) Of great interest here are the links between wind pressure fields, surface air temperature, water temperatures at various depths, and the extent and duration of sea ice.

- A discussion of the relative importance of **advection versus local events** in determining temperature and salinity at various selected geographical points. How important are events occurring off Greenland or in the

Canadian Archipelago? Why is bottom water (at say 200 m) warmer during summer on the Labrador Shelf than it is on the northern Grand Bank? Why does the CIL cross-sectional area seem to have greater annual variability on the Seal Island line than on the Flemish Cap line?

– A discussion of processes that enhance **productivity**, including a description of areas where this happens. For example, what is the role of the Labrador Shelf saddles? Why is Hamilton Bank a hot spot? Why does the shelf break remain productive through most of the year?

An overview of the most recent observations of climate and physical oceanography, accompanied by updates of certain regionally important indices, is now an accepted component of most (if not all) stock assessment meetings conducted by DFO. While this information may give meeting participants some perception of what has been happening in the air and water, the information is seldom used directly, either to adjust an input to the assessment or to assist in making a projection. Part of the reason for this is that there are not many associations between environmental change and variables of interest to the assessment (fish biology or fishery behaviour) that are sufficiently robust to be used in a projection. However, in the majority of cases a relationship, even if well established, could not be used in a projection, because the presentation of environmental data does not include a projection of the state of important variables or indices for some period (say 1 year) into the future. If, for example, water temperature were known to influence growth rate, and temperature could be projected with some degree of confidence into the next year, then a predictive equation of growth rate on temperature could be used to project growth of individual cohorts over that time interval (assuming stationarity of the relationship). There is some evidence that the autocorrelative properties of water temperature time series can be used to look ahead one year (Shelton et al. 1999; Stein and Lloret 2001). What possibilities are there for using water properties observed upstream (e.g. off West Greenland, in the Canadian Arctic, or even on the northern Labrador Shelf) to project the properties of water to the south some time in the future? How predictable are large-scale climate patterns? **Perhaps the ability to project various physical properties and indices into the future could be explored and stated**, so that fisheries biologists would have a more thorough understanding of what opportunities there may be.

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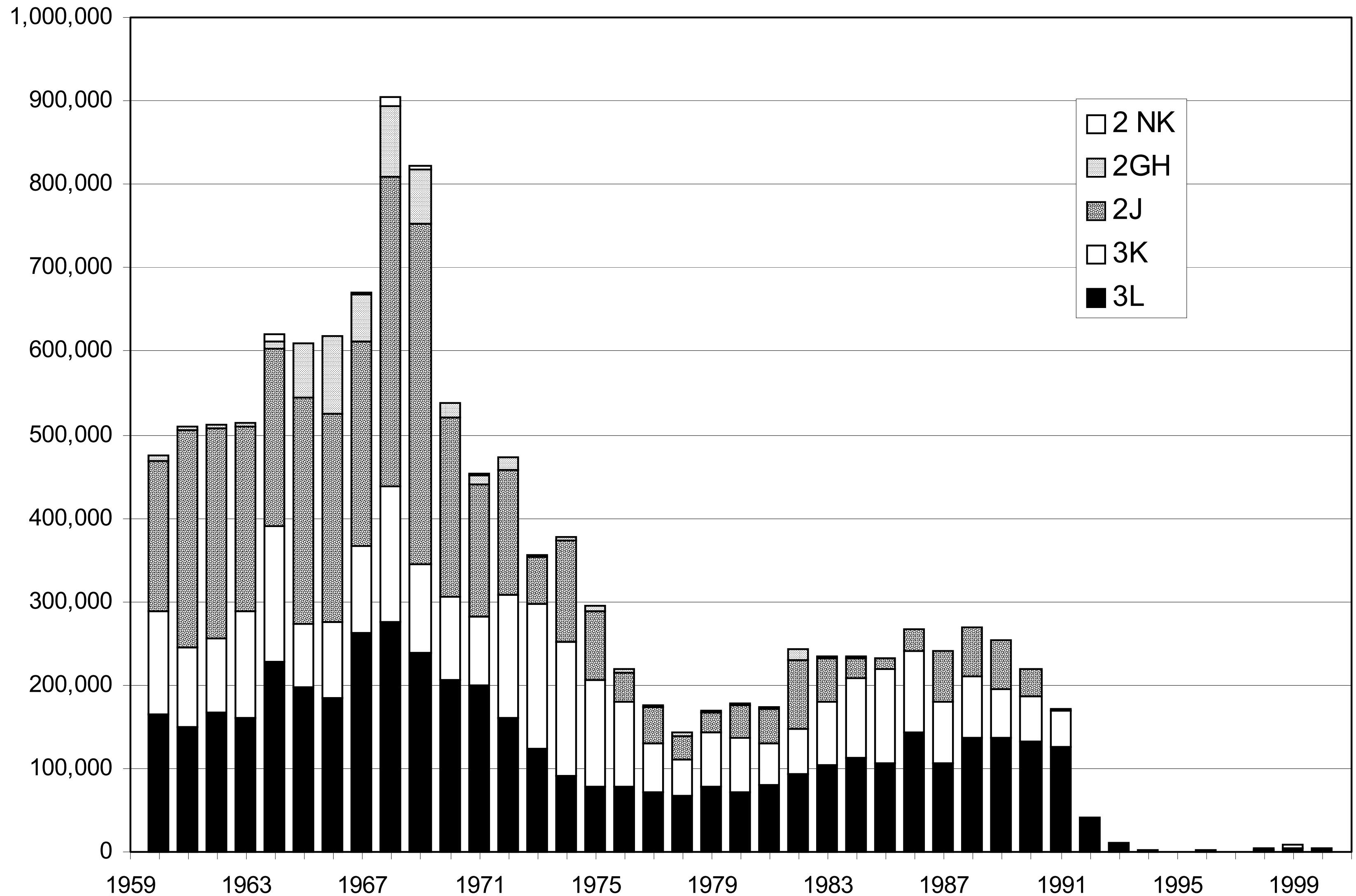

Fig. 1. Reported catches of Atlantic cod from northern Labrador to the northern Grand Bank (NAFO Subarea 2 and Divisions 3KL).

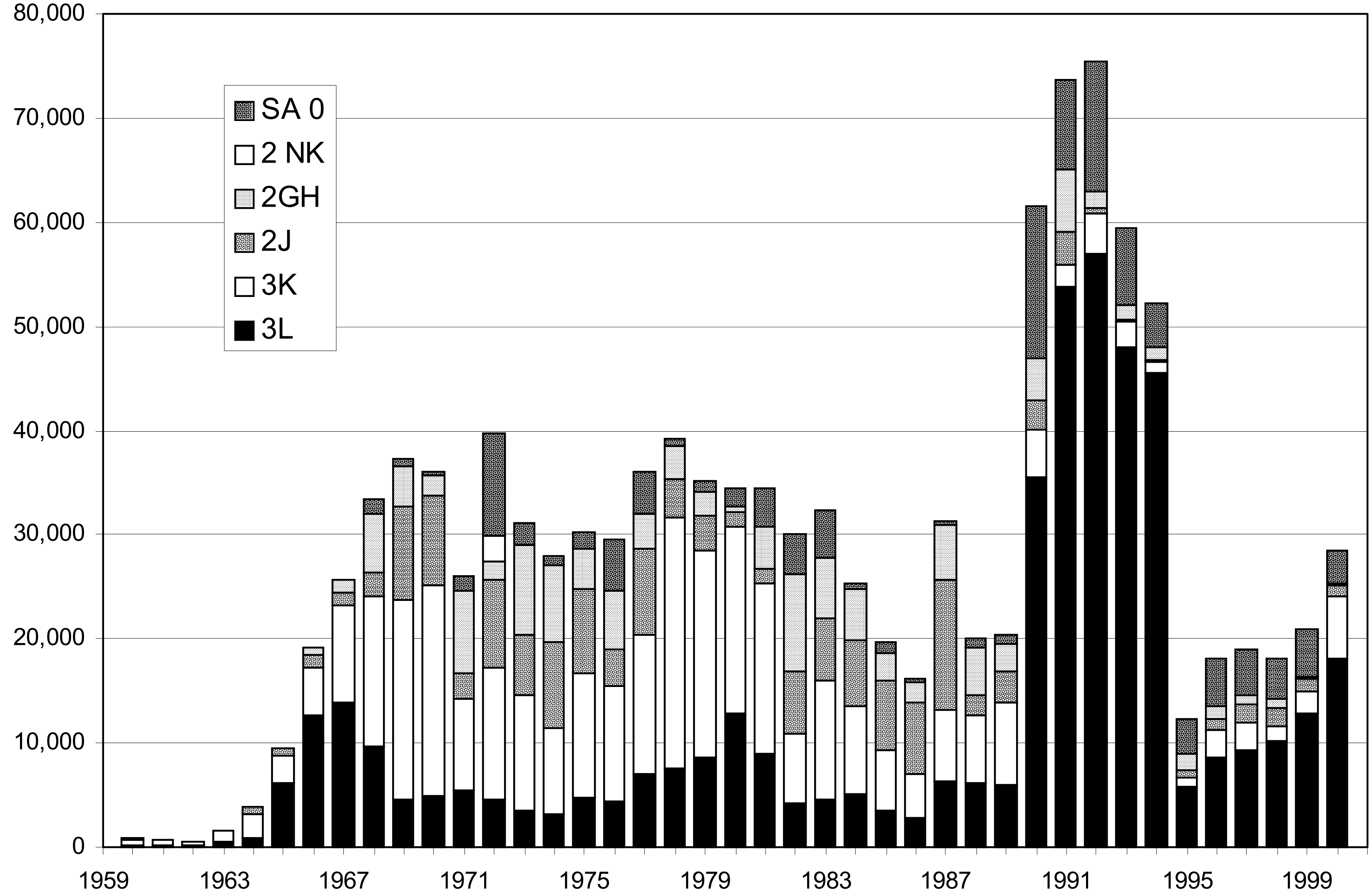

Fig. 2. Reported catches of Greenland halibut from Baffin Island to the northern Grand Bank (NAFO Subareas 0 and 2 and Divisions 3KL).

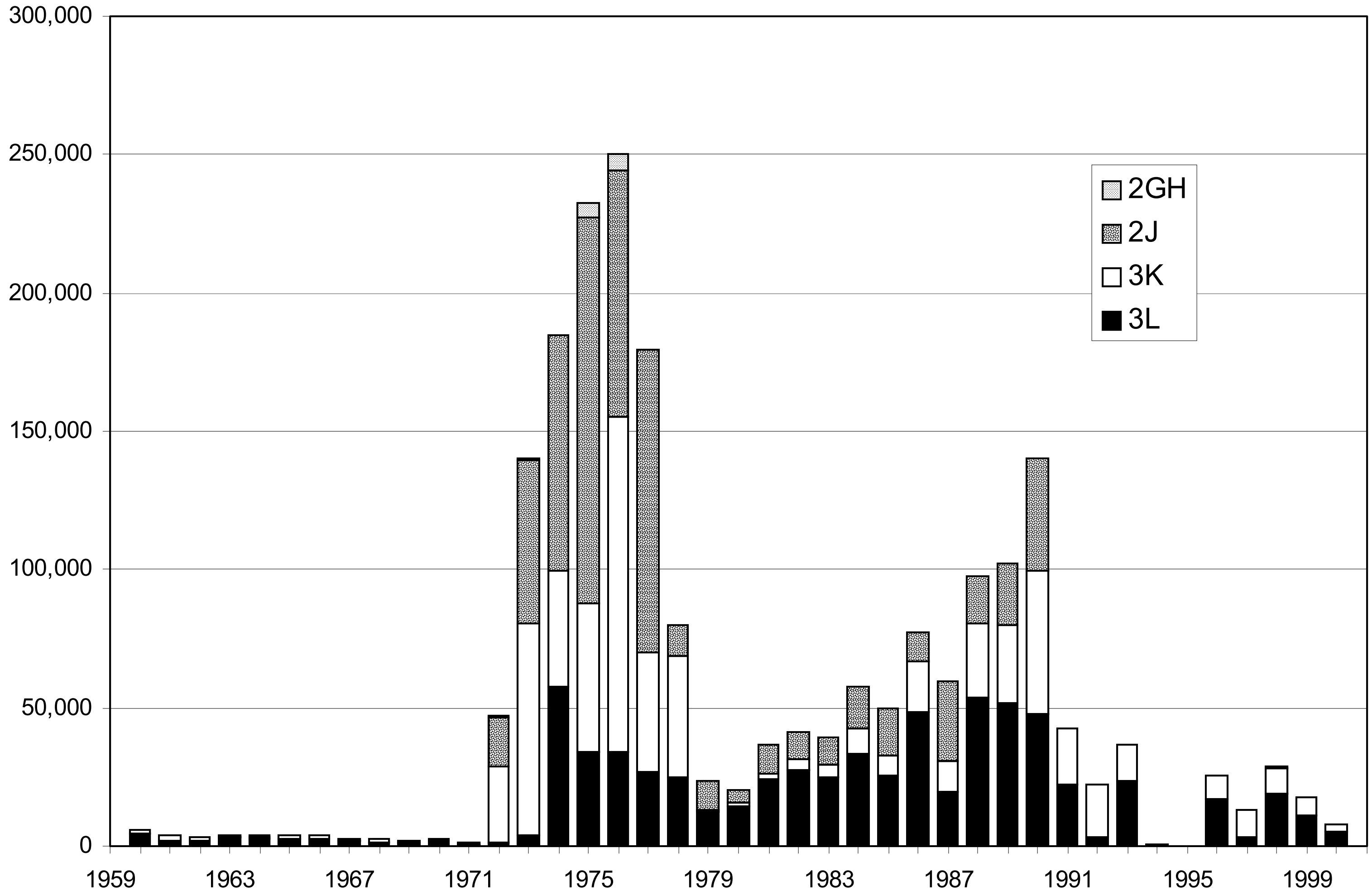

Fig. 3. Reported catches of capelin from northern Labrador to the northern Grand Bank (NAFO Subarea 2 and Divisions 3KL).

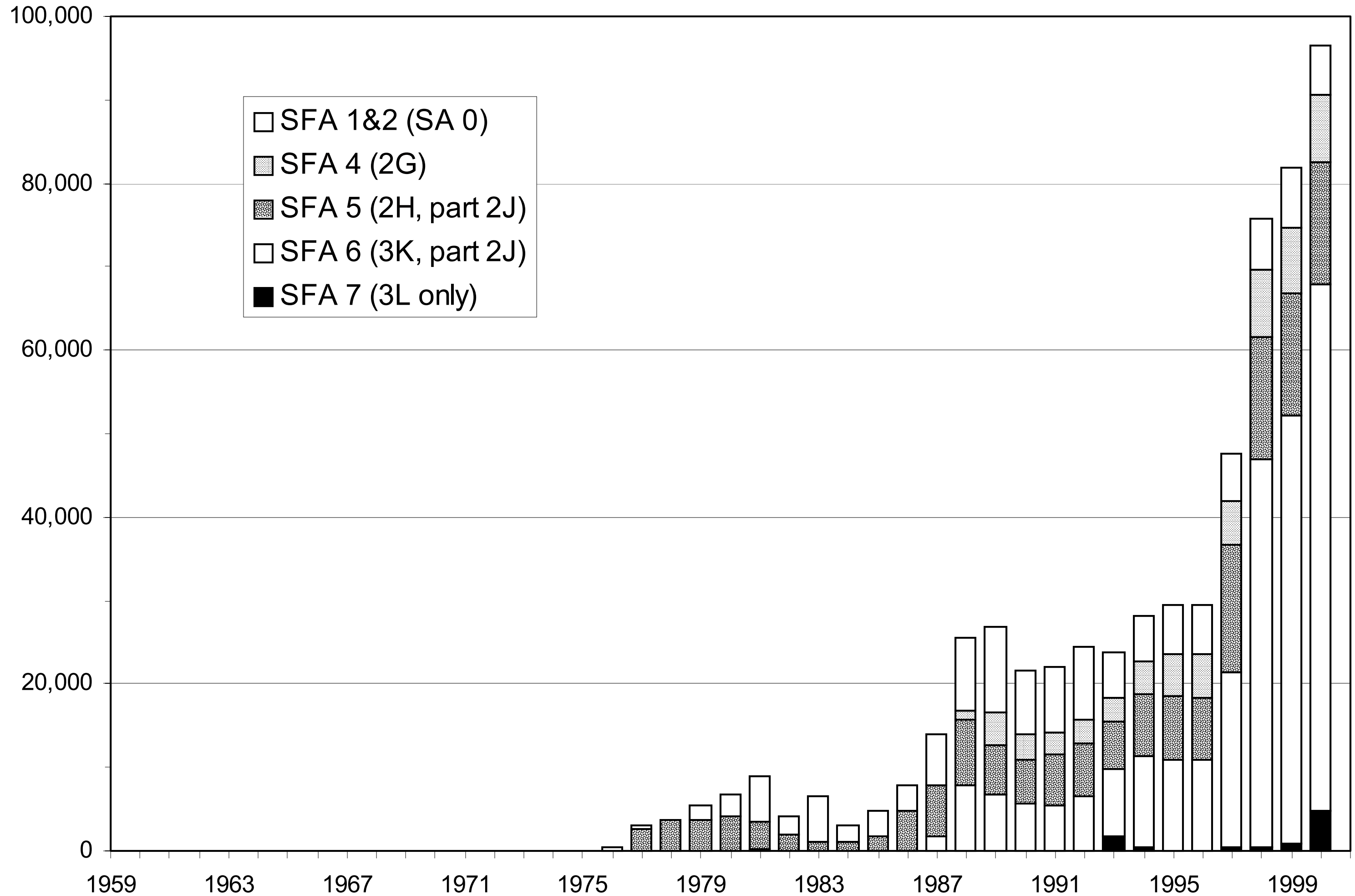

Fig. 4. Reported catches of northern shrimp from Baffin Island to the northern Grand Bank (NAFO Subareas 0 and 2 and Divisions 3KL). SFA = Canadian Shrimp Fishery Area.

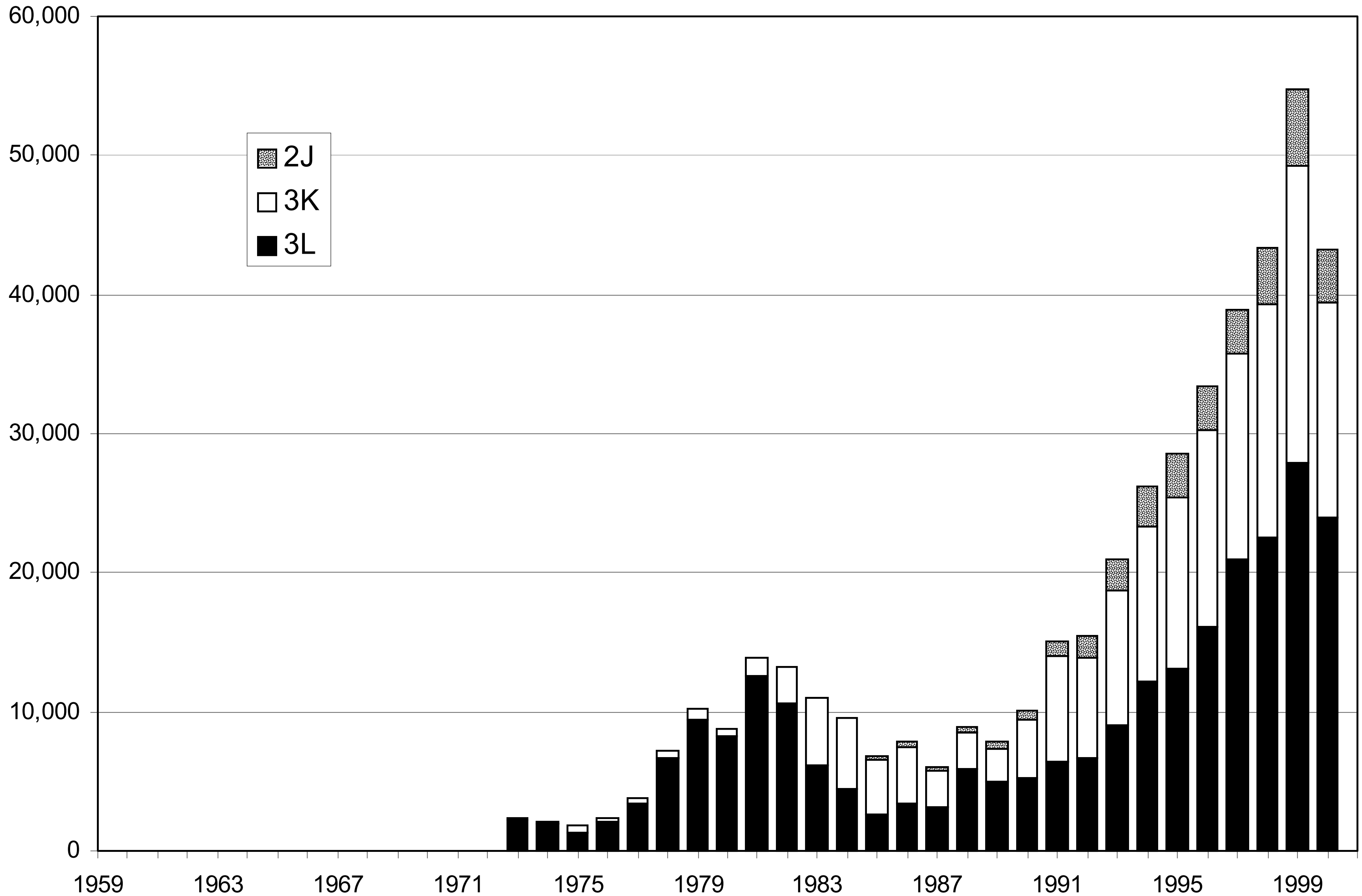

Fig. 5. Reported catches of snow crab from southern Labrador to the northern Grand Bank (NAFO Divisions 2J3KL).