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Changes in the Fisheries of Atlantic Canada Associated with Global Increases in Atmospheric Carbon Dioxide: A Preliminary Report

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CHANGES IN THE FISHERIES OF ATLANTIC CANADA ASSOCIATED WITH GLOBAL INCREASES IN ATMOSPHERIC CARBON DIOXIDE: A PRELIMINARY REPORT

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ABSTRACT

Frank, K.T., R.I. Perry, K.F. Drinkwater, and W.H. Lear. 1988. Changes in the fisheries of Atlantic Canada associated with global increases in atmospheric carbon dioxide: A preliminary report. Can. Tech. Rep. Fish. Aquat. Sci. 1652: v + 52p.

A working group of fisheries specialists of the Department of Fisheries and Oceans was assembled to consider the consequences for the fisheries of Atlantic Canada of a change in oceanographic conditions induced by a global increase in atmospheric CO_2. In a scenario with a doubling of present day atmospheric CO_2 concentrations, Wright et al. (1986) predicted several qualitative changes in the physical oceanographic features and properties of the continental shelf waters off eastern Canada. In turn, we have speculated on the impact of such changes on the location, composition, and recruitment of fish populations inhabiting the Gulf of Maine to the Labrador Shelf. For example, a general warming and freshening of the continental shelf waters is anticipated. This is expected to lead to shifts in the geographic distribution of several commercially important groundfish stocks, especially those that are presently at the extreme limits of their species ranges. Earlier arrival times and later departures are expected for pelagic species that undergo extensive seasonal migrations. Higher temperatures and increased stratification may result in less organic material reaching the bottom and tend to favor a pelagic fish community. Several published studies exist that use physical data as proxy variables for nutrient flux, advection and stratification to predict species recruitment patterns and stock size differences in the northwest Atlantic. Chief among these are the models by 1) Sutcliffe et al. (1973, 1977, 1983) that rely on river discharge, sea surface temperature, and salinity, 2) Myers and Drinkwater (1986, 1988a) who have generated stock specific annual indices of Gulf Stream warm core ring activity for several fish stocks that spawn on offshore banks on the continental shelf and 3) Iles and Sinclair (1982) who argue that the size of the larval retention area, itself defined by the Simpson-Hunter stratification parameter, is an important factor in determination of the production capacity of the stock. We use these models in conjunction with the specific physical oceanographic scenario devised to speculate on the most probable consequences to the fisheries of Atlantic Canada. We recognize the highly speculative nature of such an exercise, in part because of the uncertainties in the predicted physical changes, but also because of the limited knowledge of the processes linking the physical oceanography with fisheries. Consequently, the fisheries scenario we devise is considered to be informed speculation intended as the first step towards generating realistic predictions of future changes. Recommendations are also provided in anticipation of the question — where do we go from here?

RÉSUMÉ

Frank, K.T., R.I. Perry, K.F. Drinkwater, et W.H. Lear. 1988. Incidence des augmentations de dixoyde de carbone à l'échelle mondiale sur les pêches dans l'Atlantique canadien: Rapport préliminaire. Can. Tech. Rep. Fish. Aquat. Sci. 1652: v + 52p.

Un groupe de travail réunissant des spécialistes des pêches du ministère des Pêches et Océans a été constitué, avec mandat d'étudier l'impact sur les pêches dans l'Atlantique canadien d'une modification des conditions océanographiques provoquée par l'augmentation du CO_2 dans l'atmosphère à l'échelle du globe. Étudiant un scénario dans lequel les concentrations atmosphériques de CO_2 seraient le double des niveaux actuels, Wright et al. (1986) ont prédit plusieurs changements qualitatifs des caractéristiques et des propriétés océanographiques physiques des eaux du plateau continental de l'est du Canada. Nous avons, pour notre part, examiné L'impact de tels changements sur l'emplacement, la composition et le recrutement des populations de poissons dans la région s'étendant du golfe du Maine jusqu'au plateau du Labrador. Par exemple, on s'attend à ce qu'il se produise dans l'ensemble un réchauffement et use dessalure des eaux du plateau continental. Cette situation devrait entraîner des modifications de la répartition géographique de plusieurs stocks de poissons de fond commercialement importants, notamment ceux qui se trouvent actuellement aux limites extrêmes de l'aire de répartition de leur espèce. Des arrivées plus hâtives et des départs plus tardifs devraient être observés dans le cas des espèces pélagiques qui effectuent des migrations saissonières importantes. L'élévation des températures et la stratification accrue pourraient faire en sorte qu'une moins grande quantité de matières organiques atteigne le found et ainsi favoriser une communauté de poissons pélagiques. Il existe plusieurs études publiées dans lesquelles des données physiques ont été utilisées comme variables représentatives du flux des matières nutritives, de l'advection et de la stratification, afin de prévoir les profils de recrutement et les différences de taille des stocks dans le nord-ouest de l'Atlantique. Au premier rang de ces études se trouvent les modèles de 1) Sutcliffe et al. (1973, 1977, 1983) qui se fondent sur le débit des rivières, la température superficielle de la mer et la salinité, de 2) Myers et Drinkwater (1986, 1988a) qui ont produit des indices annuels, propres à chaque stock, de l'activité des anneaux à noyau chaud du Gulf Stream dans le cas de plusieurs stocks de poissons qui frqyent sur des bancs situés au large sur le plateau continental, et de 3) Iles et Sinclair (1982), dont l'argument est que la taille de la zone de rétention des larves, elle-même définie par le paramètre de stratification de Simpson-Hunter, est un facteur important qui détermine la capacité de production du stock. Nous utilisons ces modèles en conjonction avec le scénario océanographique physique particulier mis au point pour tenter de prévoir les effets les plus probables sur les pêches dans l'Atlantique canadien. Nous nous rendons compte de la nature hautement spéculative d'une telle démarche, en partie en raison de l'incertitude quant aux changements physiques prévisibles, mais aussi parce que peu de données sont connues sur les processus qui lient l'océanographie physique et les pêches. Par conséquent, le scénario que nous établissons doit être perçu comme une spéculation éclairée et comme la première étape d'un effort visant à produire des prévisions réalistes des changements futurs. Des recommandations sont aussi formulées concernant la voie d'action à suivre devant cette situation.

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INTRODUCTION

Overview

Several comprehensive reviews were published during the past decade concerning hypotheses that linked climate with variations in marine fish stocks (Cushing and Dickson 1976, Hempel 1978, Lasker 1978, Bakun and Parrish 1980, Akenhead et al. 1981, Bardach and Santerre 1981, Bakun et al. 1982, Shepherd et al. 1985, Sissenwine 1984, Kawasaki 1985, Report of IREP Study Group 1985). This growing volume of literature serves to illustrate the interest and concern over the influence of natural and man-induced changes in the Earth's climate on our renewable marine resources. To briefly summarize the conclusions of this work, climatic variations can affect the distribution and determine the growth and survival of marine fishes during several stages in their life histories. Environmental variation can be manifested through direct physiological effects, disease, feeding and predation processes resulting in annual increases or decreases in the abundance of fish stocks. On longer time scales and especially among stocks at the limit of their range, environmental factors have been linked to the expansion and contraction of geographic distributions, colonization of areas previously uninhabitable by a species, and alteration in the structure of ecosystems leading to local extinctions of species.

Today there is clear evidence that the concentration of atmospheric CO_2 and other "greenhouse" gases is on the rise and it appears that the CO_2 concentration may double sometime in the next century (Bolin et al. 1986). It has been estimated that a doubling of atmospheric CO_2 will produce an equilibrium global surface warming of about 3°C with associated changes in regional hydrological balances and wind forcing (Manabe and Stouffer 1980). The question of how such changes might affect oceanic conditions in the waters off eastern Canada (Figure 1) was addressed by a team of physical oceanographers at the Bedford Institute of Oceanography (see Wright et al. 1986). In light of the oceanographic scenarios presented in the Wright et al. (1986) report, a working group of fisheries specialists was assembled, at the request of the former Atlantic Research Directors Committee of the Department of Fisheries and Oceans, to consider the consequences for the fisheries of Atlantic Canada of a change in oceanographic conditions induced by a global increase in atmospheric CO_2. This report fulfills that mandate.

Our perception of the present day composition of finfish and shellfish resources on the continental shelf is largely based on commercial resource inventories (Figure 2). Such inventories utilize both fishery dependent (catch data) and fishery independent (research vessel surveys) information to monitor variability and forecast abundance of commercially important species. Given the adequate survey coverage it is possible to determine reliable estimates of the relative abundance and distribution of most of the important fish species. Such data were used by Colton (1972) to determine what effect climate change had on groundfish distributions in continental shelf waters between Nova Scotia and Long Island. Scott (1982) compiled 10 years of data from research bottom-trawl surveys to assess the depth, temperature and salinity preferences of fishes common to the Scotian Shelf and Bay of Fundy. In developing our scenario we have relied heavily on the results of Mahon and Sandeman (1985) who derived large scale patterns of fish distribution from the analysis of 13,000 groundfish survey trawl sets carried out between Cape Hatteras and Hudson Strait in the period 1970-1980.

Our approach has been to use the predicted qualitative changes in the physical oceanographic features and properties of the continental shelf waters off eastern Canada from Wright et al. (1986) to speculate on the impact that such changes might have on the location, composition, and recruitment of fish populations inhabiting the Gulf of Maine to the Labrador Shelf. For example, a general warming and freshening of the continental shelf waters is anticipated. This is expected to lead to shifts in the geographic distribution of several commercially important groundfish stocks, especially those that are presently at the extreme limits of their species ranges. Earlier arrival times and later departures are expected for pelagic species that undergo extensive seasonal migrations. Higher temperatures and increased stratification may result in less organic material reaching the bottom and tend to favor a pelagic fish community. Several published studies exist that use physical data as proxy variables for nutrient flux, advection and stratification to predict species recruitment patterns and stock size differences in the northwest Atlantic. Chief among these are the models by 1) Sutcliffe et al. (1973, 1977, 1983) that rely on river discharge, sea surface temperature, and salinity, 2) Myers and Drinkwater (1986, 1988a) who have generated stock specific annual indices of Gulf Stream warm core ring activity for several fish stocks that spawn on offshore banks on the continental shelf and 3) Iles and Sinclair (1982) who argue that the size of the larval retention area, itself defined by the Simpson-Hunter stratification parameter, is an important factor in determination of the production capacity of the stock. We use these models in conjunction with the specific physical oceanographic scenario devised to speculate on the most probable consequences to the fisheries of Atlantic Canada. We recognize the highly speculative nature of such an exercise, in part because of the uncertainties in the predicted physical changes, but also because of the limited knowledge of the processes linking the physical oceanography with fisheries. Consequently, the fisheries scenario we devise is considered to be informed speculation intended as the first step towards generating realistic predictions of future changes.

REVIEW OF THE PHYSICAL OCEANOGRAPHIC EFFECT

General atmospheric circulation models predict that doubling the atmospheric CO_2 content will result in 1) a global increase in air temperature with maxima at high latitudes (>70°N) and during the winter and 2) an increase in river run-off at high latitudes due to higher precipitation north of approximately 45°N. There is also evidence to suggest 3) a slight decrease (on the order of 10%) in the strength of the mean and variable wind stresses at temperate latitudes. Wright et al. (1986) speculated on the effects that such atmospheric changes may have on the marine environment off eastern Canada (Figure 1). Based on current understanding of the physical dynamics they suggested the following qualitative changes to Canadian continental shelf waters:

I. A general warming and freshening of the waters over the shelf.

II. An increase in the buoyancy-driven component of along-shelf flow, such as the Labrador and the Nova Scotian currents, resulting from increased precipitation, river run-off and ice melt. Increased run-off would also intensify estuarine circulation in the Gulf of St. Lawrence resulting in a stronger Gaspé Current. An earlier arrival of the seasonal salinity minimum over the shelves is expected because of the faster along-shelf currents and shifts in the timing of the freshwater addition from ice melt and river run-off.

III. Decreased cross-shelf exchange on the outer portions of the Scotian Shelf and the Gulf of Maine and increased exchange on the southern Labrador Shelf and over the Grand Banks. The latter is expected through enhanced horizontal mixing caused by an increase in current instabilities and eddies associated with a stronger Labrador Current and by reduced Ekman transport associated with the weaker predominant northwesterly winds. The predicted reduction in the cross-shelf exchange of shelf waters in the Gulf of Maine and the Scotian Shelf is based on a decrease in eddy-induced exchange because of fewer Gulf Stream rings and a decrease in offshore Ekman transport by the weaker westerly winds. The reduction in the number of rings follows from the expected decrease in the frequency and strength of the fluctuations or meanders in the Gulf Stream.

IV. Increased vertical stratification of the water column due to higher freshwater discharge, higher temperatures, and lower winds. The increase would be least in the Gulf of Maine where strong tidal mixing would partially counteract this stratification process. The Cold Intermediate Layer (i.e. the temperature minimum layer observed below the mixed layer under stratified conditions) would be shallower and warmer because of warmer winters but the increased stratification would result in it being eroded more slowly.

V. Coastal fronts will be displaced farther offshore because of increased river run-off and the shelf-break fronts will be slightly farther off the shelf because of increases in the Labrador Current and the outflow from the Gulf of St. Lawrence. The increased stratification will decrease the area of the tidally-induced well mixed areas, e.g. on Georges Bank or over Lurcher Shoals and shift the fronts toward shallower depths.

VI. In response to atmospheric warming, sea-ice extent and thickness will be reduced resulting in a tendency towards more year-round ice-free waters and later freeze-up and earlier break-up in those areas where ice remains. Regions now experiencing ice cover that would be expected to be ice-free under CO_2 induced warming are the Atlantic coast of Nova Scotia, most, if not all, of the Gulf of St. Lawrence, the Grand Banks, and the remaining waters offshore of Newfoundland.

Wright et al. (1986) point out the large uncertainties in the aforementioned atmospheric and oceanic predictions, not only in the magnitude of the responses but in some cases even in the sign of the change (e.g. the freshwater flow into the Gulf of St. Lawrence and the wind stress). These uncertainties arise because of the combination of inadequacies of the existing models and our lack of understanding of all of the important dynamical processes. However, these predictions represent the best available estimates of the possible consequences to eastern Canadian waters of doubling CO_2 concentrations in the atmosphere. Here we use this physical oceanographic scenario as a basis for discussing the effects on the Canadian Atlantic fisheries.

FISHERIES SCENARIO FOR ATLANTIC CANADA

I. Impact of Changes in Temperature and Salinity

As a result of the general warming and freshening of the waters over the Canadian continental shelf the following changes in the fisheries characteristics of these waters is anticipated:

1) Shifts in the geographic distribution of several, commercially important, resident groundfish stocks because of redistribution of populations or changing recruitment.

Redistribution

Stocks currently at the southern limit of their species distribution should experience a retraction northward whereas those stocks near the northern limit should experience an expansion northward. The situation is analogous to the changes in fish distribution that occurred off West Greenland during the first half of this century (Hansen and Herman 1965). The catches of cod at West Greenland increased from approximately 50,000 tons/yr during the 1930-40s to over 400,000 tons/yr in the 1960s. This remarkable increase coincided with large positive anomalies in sea surface temperature for the region (Figure 3). Among the many species examined by Mahon and Sandeman (1985) the following species showed a distributional pattern extending well into the northern latitudes of the geographic range considered: cod, Greenland halibut, American plaice, Northern wolffish, and capelin (Figure 4). These species are likely to experience a northward expansion of their range assuming that the waters to the north of their present distribution become warm enough for their successful colonization.

Several cold-water species whose present southern limit of distribution is in the Gulf of Maine, such as cod, American plaice, haddock, Atlantic halibut, cusk, redfish, and yellowtail flounder, are expected to be displaced to the north under warming conditions. For this reason the Gulf of Maine region may show a strong compositional change, one likely to resemble more the fish community currently distributed throughout the Middle Atlantic Bight which is dominated by species such as menhaden, butterfish, red hake, herring, and silver hake (Figure 5). These conclusions are largely based on previous studies of distributional patterns of fish stocks in relation to environmental conditions in the New England and Canadian Maritime regions by Taylor et al. (1957), Templeman (1959), Colton (1972), and Scott (1982) that are annotated in Table 1. For instance, during the warming trend in the 1940s Taylor et al. (1957) noted a northward shift in the abundance and distribution of mackerel, lobster, and menhaden and a range extension of southern-oriented species such as green crab which established a resident population north of any previous recorded location. Colton (1972), examining the cold period of the 1960s, found the range of American plaice and butterfish appeared to retract southward while species such as capelin and spiny dogfish extended their migrational ranges southward. No obvious geographical shift in the location of haddock stocks in the Gulf of Maine was apparent during this cooling period and Colton (1972) speculated that their distribution was limited more by restrictive spawning areas and appropriate bottom type than temperature. Perry and Losier (1988) have also concluded the distributions of such species as yellowtail flounder, winter flounder, and winter skate on the Scotian Shelf are determined by appropriate bottom type, and are relatively insensitive to wide seasonal variations in temperature. These documented changes in the Gulf of Maine fish stock composition associated with both cooling and warming periods attest to the transitional characteristic of the fauna in the region. In most of the cases we have reviewed above it was not clear whether or not the observed changes resulted solely from changes in migration patterns during non-reproductive portions of the life cycle. Alterations in recruitment is, of course, another possible response to changing temperatures (see below).

Seasonal changes in the relative abundance of nearshore fishes appears to be related to the annual bottom temperature regime for a given region (Tyler 1971). Annual variation in the nearshore temperature regime, measured at several sites from Chesapeake Bay to Passamaquoddy Bay, shows that the regular or year-round component of the fish assemblages becomes progressively smaller and the temporary component increases as the annual range in bottom temperature increases (Figure 6).

It should be noted that some species may respond to increasing temperatures by changing their vertical distribution patterns. Silver hake generally prefer temperatures of 6-10°C and are known to inhabit deep waters within the Gulf of Maine and the Scotian Shelf. During the warming trend through the 1940s, however, Leim and Scott (1966) noted increased catches and year round persistence of silver hake in shallow waters on Georges Bank. Cross-shelf gradients in water temperature at a given depth strata are common on the Scotian Shelf such that temperatures are higher offshore throughout most of the year (Drinkwater and Taylor 1982). Cross-shelf changes in the distribution of cold-water fishes in response to increases in temperature could, therefore, result in their prolonged concentration in the nearshore.

Recruitment

Recruitment variation is frequently explained by variation in sea surface temperatures or correlates thereof (see Table 2) with the sign of the relationship associated with the distributional characteristics of the spawning stock in question. Positive correlations between recruitment and SST's are generally evident among stocks near to their northern limit of distribution while recruitment is often inversely related to SST's among stocks resident in the southern limit of their geographic range (Sutcliffe et al. 1977, Harding et al. 1983, Leggett et al. 1984, Winters et al. 1985). For example, whereas cod recruitment variation off Greenland is positively related to water temperature, near to its southern limit in the Gulf of Maine cod recruitment is negatively correlated with sea surface temperature (Sutcliffe et al. 1977). Other species at their northern limits, such as butterfish in the Gulf of Maine and yellowtail on the Grand Banks, show positive correlations with temperature (Sutcliffe et al. 1977 and Pitt 1970, respectively) and species at their southern extremes, such as redfish in the Gulf of Maine and yellowtail flounder in southern New England, exhibit negative correlations with sea surface temperatures (redfish: Templeman 1959, Sutcliffe et al. 1977; yellowtail: Taylor et al. 1957, Sutcliffe et al. 1977, Sissenwine 1974). This reciprocity in the recruitment response to SST could contribute as much as, or even more than, redistribution to the strong compositional change anticipated in the biogeographical transition area of the Gulf of Maine (Table 3). The southern Grand Banks/southeastern coast of Newfoundland is believed to be another transitional area because of its distinct finfish and hydrographic regime (Figure 7) and the frequent observation of positive associations between temperature and recruitment (haddock: Templeman and Hodder 1965; herring: Winters et al. 1985; capelin: Leggett et al. 1984) in the region. Several instances exist showing that SST and river discharge co-vary because of the influence of freshwater on stratification and heat retention in the surface waters. Interannual variation in Quebec lobster landings has been explained by St. Lawrence River discharge lagged by nine years, with the time lag corresponding to the year of birth (Sutcliffe 1972, 1973).

Possible Mechanisms

Several mechanisms have been proposed underlying the effects of temperature on recruitment that may ultimately be linked to stock redistribution. The following is a brief review of these mechanisms.

Temperature anomalies have been commonly invoked to explain biological variation through altered growth and maturation rates of interacting populations resulting in synchrony or disynchrony in the timing of critical events in the life history (Table 4). Sub-optimal temperatures have been shown to directly cause mortality of fish eggs and larvae or to induce sub-lethal effects that can act to reduce the foraging and predator escape responses of fish larvae.

Many aspects of the life history of lobster (*Homarus americanus*) are influenced by temperature such as the rate of egg and larval development, moult frequency and recruitment (Templeman 1936). Trends in annual lobster production in the Gulf of Maine have been related to winter temperature lagged by 5-8 yr which indicates the first winter as being critical for lobster survival (Flowers and Saila 1972, Dow 1977). Harding et al. (1983) invoked an idea by Huntsman, that warm (>12°C) surface water of sufficient duration is essential for the successful completion of the larval stages of lobster, to explain patterns of variation in lobster recruitment in the Gulf of Maine.

Dickie (1955) has shown that fluctuations in the abundance of scallops (Placopecten magellanicus) in the Bay of Fundy and seasonal water temperatures for the period from 1930-1953 show a close relationship if the abundance is plotted against temperature lagged by 6 years, i.e., at the time the scallops were recruited into the population (Figure 8). High temperatures result in good settlement in the vicinity of the parent beds leading to strong year-classes and good sets. The influence of temperature is two-fold: 1) high temperatures result in rapid larval development and good survival and 2) these conditions occur when there is less exchange of water between the Bay of Fundy and the sea outside, resulting in good larval retention and minimal larval losses. Caddy (1979) analyzed a further 20 yr of data and confirmed the lagged correlation of scallop production with temperature.

Recent research in the Gulf of Maine, prompted by the Sutcliffe et al. (1977) recommendation for identification of mechanisms underlying the correlations between fish landings and SST, has demonstrated that SST during the overwintering period explained a significant proportion of the variance in the spring abundance of the ctenophore Pleurobrachia (Frank 1986). Ctenophores are jellyfish-like animals that, when abundant ($>1/m^3$), are capable of grazing down the stock of zooplankton that larval fish consume. Positive SST anomalies during January-April were coupled with the advancement of the seasonal peak in ctenophore abundance from the summer (normal time of peak abundance) to spring period. The peak period of reproduction in haddock and cod over the banks occurs from March-May (O'Boyle et al. 1984). Exact phasing of haddock reproduction and peak ctenophore abundance was observed during the spring of 1983 in the Gulf of Maine and it appears the 1983 haddock year class is the lowest on record. The possibility exists that the relationship between SST anomalies and the spring abundance of Pleurobrachia is one of the underlying causes for the negative correlations between lagged SST (span of months used ranged from Nov.-Feb.) and fish catch among the stocks of cod and haddock in the Gulf of Maine.

Studies were conducted by Anderson (1984) on Flemish Cap during 1978-82 to assess the influence of environmental factors on the distribution, abundance and growth of the early life stages of redfish (Sebastes spp.). Approximately 48% of the annual increase in surface water temperature occurs during June and July, a period during which exponential growth is normally evident among redfish larvae on the bank. An exception to this growth rule occurred in 1979 and 1981 when larval growth rates were low and high mortality was evident during May-June. Warmer than average surface water temperatures occurred during these months imposing a "physiological hurdle" that may have constituted a critical period for larval redfish survival on Flemish Cap. Anderson (1984) has put forward the hypothesis that the magnitude and rate of seasonal heating of the surface waters of Flemish Cap is an important determinant of larval mortality in redfish and, possibly, of recruitment. Interestingly, Atlantic mackerel (Scomber scombrus) egg mortality increased with the annual rate of warming of the mixed layer in St. Georges Bay, N.S. and larval mortality rates were positively correlated with temperature (Ware and Lambert 1985).

Temperature is an important factor mediating mass mortality of sea urchins (Strongylocentrotus droebachiensis) in nature where mortality is attributed to a waterborne disease which sea urchins lack natural resistance to at warm temperatures (Miller and Colodey 1983, Scheibling and Stephenson 1984, Miller 1985). High densities of sea urchins are capable of destroying vast areas of submerged seaweed when they are abundant thus eliminating the preferred habitat of lobsters in coastal waters (Breen and Mann 1976). The extent of urchin mortality may be dependent upon a cumulative temperature effect during August to November which exceeds the lower limit (8-12°C over 60 d) for transmission of the disease (Scheibling and Stephenson 1984). Mass mortalities of sea urchins caused by positive temperature anomalies appears to strongly influence the structure and stability of the rocky subtidal ecosystem off Nova Scotia.

Pauly (1980) has derived multiple linear regressions for estimating natural mortality of a population from mean environmental temperature and the parameters of the vonBertalanffy growth equation. Water temperature was positively correlated with mortality (M) in the model and several stocks in the northwest Atlantic were included in the analysis leading to the derivation of the model. The equations provide reliable estimates of M for any given fish stock and could be used to predict the influence of a warmer water regime. For example, a 2°C increase in temperature experienced by the Georges Bank haddock stock would increase the natural mortality rate from 25% to 29% assuming the other parameters remained constant.

The possibility also exists for application of the concept of "Thermal Habitat Space" to predict the impact of a warmer water regime on fish production (Christie and Regier 1988). In nature fish seek temperatures that are as close as possible to their final preferenda when food resources are not limiting. Such temperatures are generally close to those that maximize growth. Christie and Regier (1988) derived measures of thermal habitat space in lakes by integrating, over time during the summer period, the amount of bottom area and pelagic volume with water temperatures within the species' optimum temperature range. The species' specific measures, either thermal habitat area or volume, were highly successful in explaining the total sustained yield of each of four commercially important temperate freshwater species examined (Christie and Regier 1988). We advocate the application of this approach to marine species whose distributions are relatively stationary on a seasonal basis and constrained more by bottom type than other factors (e.g. haddock). Grand Bank plaice are also relatively sedentary with most returns from tagging experiments coming from localaties less than 30 miles from the release site up to 6 years after release (Pitt 1969). Given that temperature measurements could be obtained through a combination of moored thermistor chains and temperature transects and production estimates of commercial fish stocks are made on an annual basis, the test of this relationship could be made quite easily. The approach would be to define the temperature most commonly selected by each species of interest, quantify the area of water inhabited by the species in the region within their optimal temperature range during the growing season, and relate the available optimal thermal habitat area (THA) or volume (THV) to the yield of each species on an annual basis.

Fecundity, spawning date and spawning duration are also influenced by temperature (Table 4). Annual variation in March-April bottom water temperature on Georges Bank can alter haddock spawning time by a month and spawning duration is prolonged during warm years (Marak and Livingstone 1970). Considerable year to year variation in fecundity of Grand Bank haddock was evident during 1957-61 and was related to the temperature averaged over the water column at hydrographic Station 27 off St. John's, Nfld. for the period January to May (Hodder 1965). The fecundity relationships should be updated and possibly expanded given that the commercial resource assessment activities are capable of generating data on fecundity, condition factors, and diet analysis, all of which are sensitive to environmental change.

Sutcliffe (1972, 1973) found positive correlations between Quebec lobster landings and the St. Lawrence River discharge nine years earlier. The lag was interpreted as an effect of runoff on the lobster's first year of life, an observation consistent with other studies suggesting that recruitment is determined during the egg and larval period. As a result of the lag between river discharge and fish catch, predictions of Quebec lobster landings have been made based only on runoff for the St. Lawrence River system (Sheldon et al. 1982). The predictions shown in Figure 9 closely matched the actual landings for the eight years up to and including 1985 (Drinkwater 1987). A 10% increase in river runoff would result in an approximate 20% increase in lobster landings (Sheldon et al. 1982). It was originally thought that increased freshwater discharge caused nutrient enrichment which subsequently affected lobster larvae through influences on the food chain (Sutcliffe 1973). Later, the role of freshwater on stratification and increased heat retention near the surface was felt to be a more important process (Sheldon et al. 1982, Drinkwater 1987). Recent analysis shows the Sheldon et al. (1982) predictions of lobster landings from 1985 to 1987 to diverge significantly from recorded landings. The next few years will determine if this represents short term phenomena or whether the earlier relationship between St. Lawrence River discharge and lobster landings is no longer valid. In addition, it is presently thought that lobsters enter the fishery near 6 years of age and are essentially fished out by the end of the second season. This puts into question the biological significance of a 9 year lag. However, ageing of lobsters is difficult and statistically significant correlations between the Quebec lobster landings and St. Lawrence River discharge were found over a range of lags spanning 5 to 11 years, indicating a relationship between these 2 variables may still be valid.

Other lobster stocks in the Gulf of St. Lawrence have also been linked with river discharge. Bugden et al. (1982) report that the annual landings of 6 of 11 lobster districts in the Gulf were statistically related to RIVSUM with stock specific lags spanning from 3 to 11 years. The maximum correlations occurred with the Magdalen Islands stock. Sutcliffe (1983) found that the abundance of Stage I lobster larvae in western Northumberland Strait was positively related to the June discharge from the Miramichi River indicating the possible importance of smaller freshwater sources on a local scale.

Fish species are uniquely adapted to a particular suite of environmental characteristics and, for this reason, it is not surprising that a brief review of the mechanisms underlying the effect of changing temperature on fish distributions has shown a variety of species specific responses. This fact does not change the expected responses of the various fish stocks to warmer waters associated with a doubling of atmospheric CO_2. Instead, the review is intended to provide an overview of the probable pathways of change in going from the present day regime to the future "greenhouse" scenario.

2) Earlier arrival times and later departure at northern boundaries for species which undergo extensive seasonal migrations and possible year-round feeding in overwintering areas due to the anticipated milder winters.

Extensive seasonal migrations characterize several pelagic species, e.g. Atlantic salmon, mackerel, herring and spiny dogfish all appear seasonally in Canadian waters. Spiny dogfish generally do not appear until water temperatures exceed 5.5°C and then occur progressively further north with seasonal warming. Mackerel migrate south in winter, but also occur in deep slope water at intermediate depths along the Scotian Shelf. Northward spring migrations of mackerel along the Scotian Shelf and into the Gulf of St. Lawrence appear to follow the 7°C SST isotherm (Loucks 1981). Templeman and Fleming (1953) noted that mackerel were unusually common in Newfoundland waters during the 1940s possibly in response to a warming trend. The average arrival time of herring on their southern Gulf of St. Lawrence spawning grounds is linked to April SST (Messieh 1986). The seasonal progression of SST isotherms are accurate predictors of pelagic fish distributions, particularly for Atlantic salmon where the position of the 4°C isotherm explains catch variability off west Greendland (an observation which agrees with the estimated optimal temperature for the marine phase of salmon (Saunders 1986)). Collectively, warmer temperatures associated with the Greenhouse effect should increase the northward distribution of these species during the summer months and cause them to arrive earlier and leave later in the year than at present.

Continued feeding throughout the winter months is another important consequence of exceptionally mild winters and could lead to substantial additional growth during a three to four month over-wintering period normally associated with fasting (Figure 10).

3) Higher temperatures combined with increased stratification may result in lesser amounts of organic material reaching the bottom tending to favor the proliferation of a pelagic fish community.

The relative magnitudes of energy flux through the planktonic and benthic components of the food web are dependent upon both temperature and stratification. High temperatures increase phytoplankton decomposition rates which, in turn, results in the benthos receiving a smaller proportion of total energy flux (Petersen and Curtis 1980). Sedimentation rates of organic carbon and nitrogen are inversely related to stratification intensity and in strongly stratified waters most of the energy is recycled in the upper layers (Hargrave et al. 1985). Several ecosystem characteristics exist that tend to reflect the combined influence of temperature and stratification. In particular, fish species composition in warmer seas (low latitudes) is dominated by pelagic fishes while in colder waters (high latitudes) demersal fishes dominate the community. In the North Atlantic the percentage of demersal fish in commercial landings decreases from over 90% on the Labrador Shelf to about 30% in the Bay of Biscay; a striking inverse relationship is obtained when the percentage of demersal fish over this geographic range is plotted against bottom water temperature (Jones 1982). Based on this relationship a change in the mean annual bottom water temperature from 3° to 6°C would result in a 20% reduction in the percentage of demersal fish landed (Figure 11). This refers to a shift in species composition and does not necessarily represent an absolute decrease in total fish production.

II. Impact of Changes in Along-Shelf Transport

As a result of the expected increase in precipitation, runoff and ice melt due to the "Greenhouse" effect, Wright et al. (1986) suggest a slight increase in the current strengths of the inshore and offshore branches of the Labrador Current, around and over the Grand Banks and Flemish Cap, around southeastern Newfoundland, southwest along the Scotian Shelf and counter- clockwise around the Gulf of Maine. In addition, in the Gulf of St. Lawrence there should be an increase in the estuarine circulation leading to a stronger Gaspé Current and increased exchange through the Cabot Strait.

1) For those fish stocks that depend on advective dispersal of eggs and larvae for successful reproduction, changes in the time of arrival and location of offspring relative to their nursery grounds can be expected to occur.

There is growing evidence that for several finfish and shellfish species, the residual currents (primarily alongshelf) transport larvae from spawning sites to "downstream" nursery areas. If the larvae are to survive during this transit, sufficient food must exist and the larvae must arrive at the nursery area at a suitable time and size (Parrish et al. 1981). In the Northwest Atlantic there are several examples of fish populations that appear to depend on dispersal of offspring for successful reproduction. The Labrador-East Newfoundland cod stock, extending from Ungava Bay and Labrador to the northern Grand Banks and the Avalon Peninsula, spawn mainly off northern Labrador from March to early May (Templeman 1981). Larval surveys have revealed a general increase in the age of larvae southward along the Labrador Shelf with the elapsed time and the distances from the spawning sites consistent with the estimated residual current drift speeds (Templeman 1981). During late summer in the embayments of eastern Newfoundland large concentrations of juvenile cod are found very close to shore and are routinely captured during beach seining surveys (Fleming 1963; Lear et al. 1980). The larvae of several other cod stocks are believed to be advected by the mean alongshelf flows, e.g. those on the southern Grand Bank exhibit southward drift across the Bank, those from St. Pierre are carried westward toward the Gulf of St. Lawrence, and larvae spawned in the northeastern and southern regions of the Gulf of St. Lawrence are believed to be partially exchanged through advection by the mean currents (Templeman 1981). It has also been suggested that lobster spawned offshore on Georges and Browns Bank are carried by the anti-clockwise circulation within the Gulf of Maine resulting in important contributions to the recruitment off southwestern Nova Scotia (Figure 12; Harding et al. 1983; Harding and Trites 1988). The westward advection of haddock eggs and larvae (as well as the early life stages of cod) from Browns Bank towards the well-mixed regions of southwestern Nova Scotia is particularly evident in some years (Figure 13). It is noteworthy that this inshore area is also characterized by a relatively greater abundance of small zooplankton in the size range appropriate to early feeding larvae (Frank 1988). Seasonal distributions of larval herring in the coastal waters of the Gulf of Maine show that larvae spawned off eastern Maine are advected along the coast in the direction of the prevailing westward mean currents (Graham 1982; Townsend et al. 1986). In addition, Iles (1971) has demonstrated that larvae from fall spawning herring off southwestern Nova Scotia are transported northeastward by "a non-tidal inflow associated with the Gulf of Maine eddy" into the Bay of Fundy where the 10-40 mm larvae accumulate and are retained (Figure 14).

It is expected, therefore, that changes in the strength of the alongshelf currents may be important to recruitment of those stocks whose larvae undergo advective drift; however, it is unclear whether such changes will reduce or enhance survival. Increases in the strength of the currents may be detrimental either by carrying the larvae beyond their nursery grounds or by delivering the larvae prematurely, i.e. either before the peak in food abundance or at too small a size of larvae to efficiently use the available prey. If, on the other hand, food is not limiting, then a faster transit to the nursery area could enhance survival possibly via a reduced risk of predation. Another possibility is that increased current speeds could transport the larvae into warmer waters sooner which could accelerate development and possibly increase recruitment (Templeman 1981). Given the relatively small predicted change in the alongshelf currents associated with increasing atmospheric CO_2 concentrations, the lack of any statistical relationships between alongshelf currents or transport with recruitment off eastern Canada, and our limited knowledge of the mechanisms and importance of larval drift, any speculation on the response of fish recruitment to changes in alongshelf flow would be of dubious value. Further studies are required to establish possible statistical relationships and to improve upon our knowledge of larval dispersal in order to make adequate predictions.

2) Adult fishes are likely to experience little or no effect from the small alongshelf current changes that are expected.

It has been repeatedly observed that fish respond directly to, and orient in, currents. Trout (1957) suggested that water movement was responsible for observed changes in the distribution of the Arcto-Norwegian cod. Laevastu (1965) has postulated that spent fish, weakened by spawning, might be carried back to the feeding grounds by the currents and return to the spawning site a year later by swimming against the currents. It has been demonstrated that selective transport by the tidal currents was important for plaice in the Southern Bight of the North Sea (Harden-Jones et al. 1978, 1979; Arnold and Cook 1984). Such transport appears to be a mechanism enabling fish to make rapid directional movements between feeding, spawning, and nursery grounds, probably without the need for any navigational ability. It has been suggested that this may also result in a significant reduction in energy costs associated with swimming (Weihs 1978), which in the case of the prespawning migration of Southern Bight plaice may be advantageous to the survival of the population (Harden-Jones 1980). However, no significant change in tidal current strengths are predicted to result from increasing atmospheric CO_2 concentrations and the small changes in residual along-shelf currents are not expected to produce noticeable effects on adult fish.

III. Impact of Changes in Cross-Shelf Exchanges

Decreased cross-shelf exchange is expected on the outer portions of the Scotian Shelf and the Gulf of Maine due to fewer Gulf Stream rings and a decrease in offshore Ekman transport by weaker westerly winds; and increased exchange on the southern Labrador Shelf and Grand Banks resulting from a stronger Labrador Current.

1) The fish stocks inhabiting Georges Bank, Scotian Shelf, and to a lesser extent the southern Grand Banks should experience less frequent episodes of poor recruitment due to decreased warm core ring activity and associated cross-shelf exchange.

The three primary cross-shelf transport mechanisms in eastern Canadian waters are wind-driven Ekman transport (Smith and Petrie 1982), eddies associated with instabilities of the alongshelf currents (LeBlond 1982; Petrie 1987) and warm-core Gulf Stream rings (Smith 1978; Trites 1981). Anticipated CO_2-induced changes include a reduction in Ekman transport through a weakening of the wind stress, an increase in the instabilities due to a strengthening of the alongshelf currents, and a decrease in warm-core ring activity associated with a weakening of the Gulf Stream (Wright et al. 1986). Such changes are expected to directly influence the distribution of eggs, larvae and adults. For instance, Ekman transport can lower survival of eggs and larvae through offshore transport (Bailey 1981) or enhance survival through onshore transport to nursery areas (Nelson et al. 1977). Coastal and shelf break upwelling is associated with periods of offshore Ekman transport (Petrie 1983, Petrie et al. 1987) which may enhance primary production with subsequent increased survival of fish larvae and adults.

The small reduction in the alongshore winds predicted by Wright et al. (1986) is not expected to produce any significant changes in fish recruitment through lower cross-shelf Ekman transport of eggs and larvae. This conclusion is based on the results of a recent simulation study of both the Scotian and Labrador Shelves (Myers and Drinkwater 1988b). No relationship was found between simulated offshore Ekman transport of eggs and larvae and recruitment indices in the ten fish stocks investigated, which included cod, haddock, redfish, American plaice, silver hake, herring, and argentine. The eggs and larvae of only a few stocks were calculated to be transported beyond 50 km offshore of their spawning site whereas the displacement distance was most frequently well inside of 50 km. Vertical migration has been reported for plaice and argentine larvae and incorporating this behaviour into the simulation model resulted in a significant reduction in the probability that horizontal advection by Ekman transport would affect their recruitment.

Not enough is known about the influence of food supply on recruitment variation among fish stocks in Canadian Atlantic waters to determine if changes in primary production due to wind-induced upwelling at the coast (Petrie et al. 1987) or the shelf break (Petrie 1983) will be important to recruitment. A reduction in upwelling may, however, reduce commercial catches of some fish species through changes in availability. For example, Rose and Leggett (1988) have demonstrated that cod trap catches along the north shore of the Gulf of St. Lawrence are directly linked to wind-induced temperature changes. Immediately after the onset of upwelling events cod catch increases dramatically. Peaks in catch (up to 1500 kg/d) coincided with maximum rates of decline in temperature and currents indicative of upwelling. Cod in this region preferred temperatures ranging from 0.5 to 8.5°C and were generally absent from waters having temperatures outside of this range (Rose and Leggett 1988).

The predicted increase of instabilities at the offshore edge of alongshelf currents (Wright et al. 1986), e.g. the Labrador Current (LeBlond 1982) and the Nova Scotian Current (Petrie 1987) implies enhanced horizontal mixing and cross-shelf exchange. In spite of the fact that these instabilities have obvious potential as a mechanism for horizontal mixing their relative importance in mixing on the continental shelves is not well established. Consequently, their influence on the early life stages of finfish and shellfish and on the nutrient budget of the shelf waters is unknown.

Warm-core rings, generated from meanders in the Gulf Stream can entrain large volumes of water from off the continental shelves from the Grand Banks to the mid-Atlantic Bight. It has been hypothesized that shelf water entrained by such features may transport sufficient quantities of fish eggs and larvae to significantly reduce recruitment (Colton and Anderson 1983; Wroblewski and Cheney 1984). A simulation model was developed by Flierl and Wroblewski (1985) that also suggested rings might exert a negative impact on recruitment. Recently, Myers and Drinkwater (1988a) assessed the hypothesis that entrainment of shelf water by warm core rings (WCR's) reduces recruitment of marine fish stocks through offshore transport of eggs and larvae. Weekly satellite images for 1973-1986 were used to generate a time-series of the positions and numbers of WCR's from the mid-Atlantic Bight to the Grand Banks. Increased WCR activity and decreasing distance of WCR's from the shelf break (200 m isobath) reduced recruitment in 17 out of the 19 groundfish stocks examined. The analysis included species such as cod, pollock, haddock, redfish, yellowtail flounder, and silver hake. The waters on the southern Scotian Shelf and Georges Bank are particularly susceptible to entrainment by Gulf Stream rings. Larvae spawned in water 100 km inshore of the shelf break can potentially be entrained out into the Slope Water region (Smith 1978; Trites 1981) and lost to the shelf. Recruitment patterns among pelagic stocks showed no consistent relationship with WCR activity. If all else were equal the predicted decrease in WCR number associated with a doubling of atmospheric CO_2 suggests a greater probability of years of strong recruitment in groundfish stocks south of 45°N (Table 5). This contrasts with the effects on squid. Rowell and Trites (1985) speculated that squid larvae spawned off the southeastern United States seaboard are transported northward by the Gulf Stream and subsequently carried towards the Scotian Shelf and Grand Banks by WCR's. Therefore, any decrease in the strength of the Gulf Stream and reduction in rings would result in fewer squid off Canada's continental shelves.

IV. Impact of Changes in Stratification

Associated with a doubling of atmospheric CO_2 is increased vertical stratification of the water column due to higher freshwater discharge, higher temperatures, and lower winds. Because the effects of reduced wind mixing and increased surface buoyancy input reinforce each other, the changes in stratification may be particularly significant.

1) <u>Increased duration of seasonal stratification may lead to predominance of dinoflagellates over diatoms in coastal waters during the annual cycle which, in turn, could lead to an overall reduction in energy available for fish production due to an increase in the number of steps in the food chain.</u>

The physical environment significantly affects dominance among different size groups of phytoplankton (Greve and Parsons 1977). Mixing and high nutrients promote the dominance of relatively large (>100 µm), fast growing diatoms that are common to coastal waters. Decreased turbulence even when nutrients remain high decreases the growth rate of diatoms by increasing losses due to sinking. The net effect of increased water column stratification would shift the growth advantage from large diatoms to smaller (5-25 um) dinoflagellates and microflagellates that are commonly abundant in oceanic locations. The latter group are better able to maintain their vertical position in a stratified water column and utilize nutrients effectively at low concentrations. It is believed that phytoplankton cell size affects the efficiency of energy transfer to harvestable fish resources, since dinoflagellate-based food chains appear to require one or two additional energy transfers to reach a given sized consumer than do diatom-based food chains (Ryther 1969). Given a transfer efficiency of organic matter between trophic levels from 10-20% it has been estimated that a 100-fold lower fish production exists in oceanic compared to coastal and upwelling waters (see Figure 15). The expectation, therefore, is for the magnitude of future fish production on the continental shelves to shift slightly towards a more "oceanic" character relative to the present day "coastal" one we now profit from.

Maintenance of an annual time series of the seasonal diatom/dinoflagellate ratio on continental shelf waters could provide an early warning signal for significant environmental changes. In fact, one hypothesis advanced to explain changes in the fish stock composition of the North Sea during the 1960's and 1970's invoked climate induced changes in the size and composition of phytoplankton and zooplankton as a determining factor (Hempel 1978). Such alterations in the base of the food chain may be symptomatic of future changes at levels higher in the food chain. Kerr and Dickie (1984) advocate examination of changes in fish production systems by reference to their characteristic size spectra. For instance, smaller zooplankters tend to be more resistant to increasingly acidic conditions therefore community size-spectra could provide useful indicators of effects of acid precipitation on poorly buffered lakes (Sprules and Knoechel 1984). Deformations of characteristic size-spectra may provide a useful, sensitive, early-warning criterion for monitoring and assessing the health of ecological communities (Kerr and Dickie 1984). It is unfortunate that the Continuous Plankton Recorder program, which has been used to study variation in the abundance, distribution and composition of the plankton (both phyto- and zooplankton) in relation to the physical environment along standard sampling routes throughout the northwest Atlantic from 1959 to present (Figure 16), has been discontinued in the Gulf of Maine region. Preliminary analysis of some of the accumulated data shows a weak inverse relationship between monthly anomalies of total copepod abundance and SST's in the Gulf of Maine region during 1981-1983 (Figure 17). If such alterations in the base of the food chain prove to be symptomatic of future changes at levels higher in the food chain then a call for reinstatement of the Gulf of Maine CPR route, and possibly the establishment of new routes in the Northwest Atlantic, is in order.

2) <u>Decreased production of the Northern cod stock in NAFO Div. 2J3KL due to the stratifying influence of increased freshwater discharge from Hudson Bay and suppressed mixing within Hudson Strait resulting in lower nutrient availability on the Labrador Shelf.</u>

An association has been established between the effects of Hudson Bay runoff on the cod stock complex of southern Labrador Shelf, northern Newfoundland and the northern Grand Bank (Sutcliffe et al. 1983) in a manner similar to previous work on the biological effects of freshwater runoff from the Gulf of St. Lawrence (Sutcliffe et al. 1977). These investigators demonstrated that summer depth averaged salinities to 50 m for each of the first three years of the life of cod accounted for 80% of the variation in abundance of the cod stock complex off Labrador and Newfoundland. High cod abundance coincided with high salinity water (i.e. during years of low runoff) when, it was argued, there were more nutrients available in the surface layers and biological production increased. They hypothesized that high river discharge into Hudson Bay causes increased stratification and suppresses vertical mixing in the Hudson Strait region. This leads to fewer nutrients in the near-surface waters (signalled by lower salinity), low primary production and a subsequent decrease in production of the Northern cod stock. A decremental change in salinity of 0.4, say from 32 to 31.6, would result in a 50% reduction in the abundance of 2J3KL cod according to the Sutcliffe et al. (1983) model.

V. Impact of Changes in Frontal Locations

The fronts (i.e. coastal, tidal, shelf-break) in the coastal and shelf waters off eastern Canada will be differentially affected by a doubling of atmospheric CO_2 such that coastal fronts will be displaced farther offshore with increased coastal run-off, and the shelf-break fronts will be displaced slightly farther off the shelf with a stronger Labrador Current and increased outflow from the Gulf of St. Lawrence. Small shifts in the position of tidal fronts toward shallower water and a decrease in the areal extent of vertically well-mixed areas is expected.

1) <u>Since the spawning locations and production capacity of many marine fish stocks are frequently associated with tidally-mixed regions any process reducing the size of such areas should result in reduced fish production.</u>

Increased stratification will decrease the area of tidally-induced well-mixed areas, e.g. on Georges Bank or over Lurcher Shoals and shift the fronts toward shallower depths. Iles and Sinclair (1982) show that the size of such well-mixed areas (called a larval retention area), whose perimeter is defined by the frontal location, is positively correlated with the mean abundance levels of herring stocks throughout the Gulf of Maine. A quantitative relationship was established between spawning stock size in metric tons and size of the respective larval retention area (km²) among four herring stocks, three of which reside in the northwest Atlantic (Figure 18). The increase in vertical stratification in the Gulf of Maine would be expected to reduce the areal extent of well mixed waters and possibly cause a reduction in herring stock size. Cod and haddock are known to spawn in eddies associated with the offshore banks in the Gulf of Maine (e.g. Georges and Browns Bank), although no similar stock size/larval distributional area relationship has been developed for these species.

VI. Impact of Changes in Sea ice Distribution

The warmer climate associated with a doubling of atmospheric CO_2 should tend to produce more year-round ice-free waters. Also later freeze-up in the fall and earlier spring and summer break-up is expected in those areas which continue to freeze over during winter.

1) <u>Aquacultural development in the nearshore regions should increase due to higher temperatures and especially in those areas presently limited by sea ice conditions.</u>

Aquaculture activities can only be considered in areas where there are no physiological limitations on finfish or shellfish production and where there are no physical limitations imposed on the farming operation. Increasing nearshore temperatures resulting from the "greenhouse" effect could result in increased production of species in established farming operations due to the prolonged availability of temperatures near to those optimum for growth. Cultivation of new species of temperate and sub-tropical origin could conceivably result from a warmer nearshore temperature regime as well. Sea ice has restricted the development of fish farming operations throughout the Canadian Maritimes and especially in the Gulf of St. Lawrence (Figure 19). It is noteworthy that Wright et al. (1986) suggest that there will be an increased occurrence of winters without ice cover in the Gulf of St. Lawrence and consequently the geographic limits for potentially viable commercial operations for salmonids, oysters and scallops could thus be substantially expanded (Figure 19). The review by Scarratt et al. (1987) should be consulted for further details on climate impact on aquaculture in Atlantic Canada.

SUMMARY

Given the predicted qualitative changes in the physical oceanographic features and properties of the continental shelf waters off eastern Canada due to increases in the atmospheric CO_2 concentrations as contained in Wright et al. (1986), we have predicted the following changes in the fisheries component for this region:

1. Northward and possibly shoreward displacement of several commercially important, resident groundfish stocks (the length scale of change cannot be specified).
2. Expansion of warmer-water species currently uncommon in our waters from localities south of the Gulf of Maine.
3. Earlier arrival and later departure times at northern boundaries for species (mainly pelagic) which undergo extensive seasonal migrations; year-round feeding in overwintering areas is a distinct possibility.
4. A tendency for changes in fish species composition from groundfish to pelagics due to the anticipated reduction in the amount of organic material reaching the bottom that fuels the benthic food web.
5. Changes in the time of arrival and location of offspring relative to their nursery grounds for those fish stocks that rely on advective dispersal of eggs and larvae for successful reproduction.
6. Less frequent episodes of poor recruitment for those fish stocks inhabiting Georges Bank, Scotian Shelf and the southern Grand Banks.
7. Reduction in total fish production due to changes in phytoplankton species composition (diatom to dinoflagellates) and the associated increase in the numbers of steps in the food chain.
8. Decreased production of the cod stock complex of southern Labrador Shelf, northern Newfoundland and the northern Grand Bank (i.e. NAFO Div. 2J3KL).
9. Reduction in the mean abundance levels of stocks whose spawning locations are associated with tidally-mixed regions.
10. Increased development of nearshore regions for aquaculture activities.

There are large uncertainties associated with each of the predictions. This reflects the lack of quantitative predictions in the physical oceanographic scenario by Wright et al. (1986) and limitations in state-of-the-art marine ecology and fisheries oceanography. The lack of quantitative physical data necessitated a single factor approach to the problem when some of the predicted physical changes could quite conceivably interact to produce no effect (e.g. increased temperatures counteracting increases in along-shelf flows with respect to prediction #5 above).

We have relied heavily on the published literature in developing our scenario. Emphasis was also given to studies conducted in Canadian Atlantic waters or to those pertaining to species known to occur there but studied in other regions. For this reason we believe there is value in this document independent of whether or not the physical oceanographic scenario is correct. As the results of new studies become available or when regional physical (and biological) models become more exact one should be able to more easily incorporate this new information given the extensive literature review. Several of the studies reported on dealt with underlying mechanisms and, in this sense, our report is open ended.

Recent advances in marine ecology and fisheries reflects the integration of several distinct disciplines such as biology, genetics, physical oceanography and geology. Needless to say, the problems are complex and those dealing with recruitment variation and fish production alluded to in this document are controversial and far from being fully resolved. For example, it is not clear whether or not alterations in recruitment or changes in migration patterns during non-reproductive portions of the life cycle will be responsible for the anticipated northward displacement of our resident groundfish stocks. Also, there is disagreement on the role that circulation patterns play in larval dispersal of shellfish and finfish stocks.

RECOMMENDATIONS

Our working group was not asked to provide any recommendations, but we feel justified in doing so given our experience in completing this difficult exercise and in anticipation of the question — where do we go from here?

1) Development of some type of biological monitoring scheme (and possibly a physical oceanographic one) is deemed necessary. Characteristics of the environment that we need to monitor are based on a rational understanding of the processes linking fish stocks to their environment. The summary tables (Tables 1, 2 and 4) of published fisheries literature relevant to Canadian Atlantic waters is intended to provide an up-to-date assessment of this knowledge base.

a) Keeping a watchful eye on those fish stocks presently at the limit of the distributional range for their species is advised since they are the most likely candidates for early detection of environmental change. Updating of the groundfish trawl survey data each decade or less in a manner consistent with the analysis of Mahon and Sandeman (1985) is advised.

b) For species that are very abundant but poorly represented in groundfish trawling surveys and that are known to respond rapidly to changes in the structure of fish communities (e.g. sand lance in the mid-Atlantic Bight/Georges Bank region, Sherman et al. (1981); Arctic cod and squid along the Labrador Shelf and northeast Newfoundland coast, Vesin et al. (1981)), very little biological data is presently available. We recommend that this situation be corrected given that these species are percieved to be of great ecological importance.

c) Continued characterization of size-spectra of fish production systems is advocated because they appear sensitive to environmental change and could thereby provide an early warning system.

d) Commercial resource assessment activities should be generating, on a routine basis, data on fecundity, condition factors (e.g. fat content), and diet analysis all of which are sensitive to environmental change.

e) One of the physical properties mechanistically related to changes in fish production and the structure of fish communities is stratification. Monitoring this property of the continental shelf waters to provide descriptions of interannual variability is advised. The proper design of any such physical oceanographic monitoring program is a difficult problem and Sinclair et al. (1987) should be consulted for an overview of this topic.

2) An acceleration of multidisciplinary research activity on basic and applied fisheries problems to substantially broaden our limited information base.

a) Improvements in our knowledge of which events in the life cycle of fishes are critical and exactly when they occur are needed in order that relevant measures of environmental influence can be made.

b) Simulation modelling is viewed as an effective way to integrate the results of both physical and biological studies leading to a coupled climate-ocean-fish production model. Advancement of such models is encouraged.

c) Several research opportunities in nature afforded by climate change are envisioned such as those associated with extensions of species ranges and possible new predator/prey relationships. Researchers should be encouraged to capitalize on these opportunities.

3) Our working group was given the mandate to assess the impact of the Greenhouse effect on the Canadian Atlantic fisheries and, as such, we did not address the immediate nearshore zone. Several commercially important marine finfish and shellfish periodically utilize estuarine and riverine habitats for spawning or during the early life history for nursery areas. Sea level changes, altered shoreline configurations, etc. could impact on these species. A separate study of this aspect of the climate change problem should be considered.

a) The fisheries working group did not address marine mammals and certain elements of the physical oceanographic scenario may impact directly on their growth and survival. For example, seals may be affected by the expected tendency for more year-round ice-free waters associated with doubled atmospheric CO_2. A separate study dealing with marine mammals and climate change should be considered.

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FIGURE LEGENDS

Figure 1. Map showing major oceanographic regions considered in this report.

Figure 2. Commercial catch composition during 1983 of various species from selected regions of Atlantic Canada. Catch information compiled from NAFO SCS Docs. 84/VI/22 and 85/9. Total annual species catches less than 500 t were not included. The NAFO Divisions contained within the geographic areas considered were as follows: Labrador Shelf-2J,3K,3L; Flemish Cap-3M; Grand Bank-3N,3O; Gulf of St. Lawrence-3Pn,4R,4S,4T, 4Vn; Scotian Shelf-4Vs,4W,4X; Gulf of Maine-5Y,5Ze,5Zw.

Figure 3. International catches of cod at West Greenland from 1930 to 1972 and the corresponding sea surface temperatures (5 year running means) for this region from 1876 to 1974.

Figure 4a. Thirty nautical mile divisions of the continental shelf from Cape Hatteras to Hudson Strait lying approximately normal to the shelf edge. Data from about 13,000 groundfish survey trawl sets made between 1970 and 1980 were separated into two depth zones (50-200m and greater than 200m) and aggregated within these divisions by Mahon and Sandeman (1985). Fish distributional patterns were generated from this analysis by determining percent occurrence in the bands.

b. Percent occurrence of several species in relation to the south to north gradient of bands. This group of species show distributions that extend well into the northern latitudes.

Figure 5. Percent occurrence of several species in relation to the south to north gradient of bands. These species show distributional patterns indicative of a southerly orientation within the total geographic range considered.

Figure 6. Percentage of fish fauna comprised of regular, seasonal and occasional species at different latitudes and associated annual bottom temperature ranges, adapted from Tyler (1971). Definition of faunal components: regulars - species present year round, seasonals - species absent during part of the year, and occasionals - species occurring irregularly and in low numbers.

Figure 7a. The four major clusters of bands using the occurrence of fishes at depths of 50-200m (taken from Mahon and Sandeman 1985). The major grouping of bands were a southern group (a) extending from Cape Hatteras to Cape Cod, a southern central (b) group extending from Cape Cod to the Scotian Gulf in the middle of the Scotian Shelf, including the Gulf of Maine and Georges Bank, a central group (c) extending through the rest of the Scotian Shelf across the Laurentian Channel and down the eastern side of this channel to the Tail of the Grand Bank, and a northern group (d) extending from the Tail of the Grand Bank northward to Cape Chidley.

b. Depth-averaged temperature (April-September) roughly corresponding to the 30 nm bands in Figure 4 in the 50-200m depth range. Values are long-term means for the period 1910-1982.

Figure 8. Annual catch per boat of scallops from the Digby fishery and temperature at 90 m from Prince Station No. 5, six years previous (taken from Dickie 1955).

Figure 9. The observed, calculated and predicted annual catches of lobster from Quebec. The calculated catch was determined from a linear regression with discharge from the St. Lawrence River system. The predicted values were also based on the regression.

Figure 10. Duration of the winter fasting period of Baltic herring in the Gulf of Riga in the years 1952-1955 according to Nikolajev (cited in Laevastu and Hela 1970). Shaded areas refer to the number of feeding fishes. Note that during the mild winter of 1951-1952 the herring continued to feed throughout the winter which resulted in substantial growth. Compare this to the severe winter of 1953-1954 when the percentage of herring which stopped feeding rose to 100% for up to four months.

Figure 11. Relationship between annual mean bottom water temperature and percentage demersal fish in commerical landings for several geographic regions (after Jones 1982) from the Labrador Shelf to Region 3 (Bay of Biscay).

Figure 12. Projected dispersal of lobster larvae from Browns Bank during a) the first week of July (approximate first hatch date) and b) the first week of August (approximate median hatch date). Percentage of the total surface drift-bottle returns

are also shown for each region (after Harding and Trites 1988).

Figure 13a. A general model of the distribution of haddock eggs, larvae and juveniles originating from Georges bank during February-April and Browns Bank during March-May (after Grosslein and Hennemuth 1973).

b. Centre of mass of the horizontal distribution of haddock eggs (Stages I-IV according to Laurence and Rogers 1976) and larvae (EL) calculated from a May 1985 survey.

c. Same as b) except for cod eggs (E), larvae (L) and pelagic juveniles (J).

Figure 14. Distribution maps of herring larvae during the periods 7-10 October, 28-30 October, and 14-17 Novemer 1969, generated from 30 minute tows of an Isaacs-Kidd 2-m trawl. Units are catch/tow (after Iles 1971).

Figure 15. Hypothetical relationship between the ratio of diatoms to dinoflagellates in passing from weak to strongly stratified waters and the expected level of fish production associated with oceanic waters where the diatom/ dinoflagellate ratio is low, and coastal waters where the reverse is the case.

Figure 16a. Two routes off the east coast of North America sampled monthly with the Hardy Continuous Plankton Recorder (CPR) from 1961 to 1984. CPR's with 225 X 235 um mesh are towed at 10 m depth by merchant ships, Ocean Weather ships, and Coast Guard vessels. Temporal and spatial variability in phyto-, zoo-, and ichthyo- plankton species composition and abundance are data products generated from such surveys. MC - Massachusetts to Cape Sable, approximately 426 km; MB -New York towards Bermuda, approximately 500 km.

b. Location of 1563 CPR samples collected along the MC route from 1961-1984 (after Jossi and Smith 1984).

Figure 17a. Monthly anomalies of total copepod abundance during 1981-1983 relative to the 1961-1982 long-term monthly means derived from the CPR survey along the MC route. Data from Jossi and Smith (1984).

b. Monthly SST anomalies from Yarmouth region relative to 1971-1982 long-term mean. Temperatures contained in the area bounded by southwestern Nova Scotia, eastern Jordan Basin and northern Browns Bank was designated as falling within the Yarmouth area.

Figure 18a. Distribution of herring larvae shortly after hatching in the Gulf of Maine region.

b. Distributions of the Simpson-Hunter stratification parameter.

c. Relationship between herring spawning stocks size and the size of the larval retention area. Note: a), b) and c) from Iles and Sinclair (1982).

Figure 19. Average spring ice conditions in the Canadian Maritimes and the present day geographic limits for potentially profitable commercial operations for marine species of importance for aquaculture development (after Scarratt 1987).

Table 1. Published studies providing evidence that physical factors influence finfish and shellfish distributions on seasonal and annual time scales. Summary restricted to studies conducted in or adjacent to Canadian Atlantic.

Source	Location	Physical Factor	Response
Templeman & Fleming (1953)	Newfoundland coastal waters	St. John's, Nfld., air temperature and water temperature record at St. Andrews, N.B., warming trend of 1940s	qualitative positive correlation of annual temperature to abundance (catch, sightings) data on mackerel, lobster, squid, capelin, and cod
Taylor *et al*. (1957)	Gulf of Maine	temperature: warming trend of the 1940s	i) northward shifts in abundance and distribution of mackerel, lobster, yellowtail flounder, menhaden, whiting ii) range extension of southern species (eg. green crab)
Templeman (1959)	Gulf of Maine	temperature	larger populations of redfish in the Gulf of Maine were correlated with low temperatures
Haynes & Wigley (1969)	Gulf of Maine	bottom temperature	high temperatures prevent northern shrimp from extending geographic range south and west of Georges Bank-Cape Cod region; no apparent relationship between shrimp distribution within Gulf of Maine and temperature
Pitt (1970)	Grand Bank	temperature	increase in yellowtail flounder between 1961-68 coincided with warmer bottom waters and demise of haddock in the region which have similar diet
Colton (1972)	continental shelf waters from Nova Scotia to Long Island	temperature: cooling trend from 1953-1967	i) slight southward shifts of American plaice (extension) and butterfish (retraction) ii) no obvious change in geographic distribution of haddock and yellowtail flounder; apparently they are restricted more by bottom type iii) capelin appeared in Bay of Fundy iv) large numbers of spiny dogfish migrated south of Cape Hatteras in winter

Table 1. (Continued)

Source	Location	Physical Factor	Response
Coutant (1977)	field and laboratory	cod, haddock (also several other marine and freshwater species)	summarizes information from field and laboratory studies on temperature selection, final temperature preferenda, and upper and lower avoidance temperatures
Fournier (1978)	Northwest Atlantic	temperature front/ shelfbreak zone	Canadian and foreign fishing vessels, spotted by reconnaissance aircraft during 1972, clearly concentrated along shelf edge suggesting frontal zone possesses significant biological properties
Loucks (1981)	Scotian Shelf/Gulf of St. Lawrence	7° C SST isotherm	northeastward spring migration of Atlantic mackerel coincides with progression of 7° C isotherm
Scott (1982)	Scotian Shelf/Gulf of Maine	bottom temperature, salinity	preferred temperature and salinity ranges established for 31 common groundfish species during 1970-79 period (eg. cold-water flatfishes: yellowtail, American plaice, Greenland halibut; warm-water: winter flounder, witch, Atlantic halibut)
Tremblay & Sinclair (1985)	Gulf of St. Lawrence	bottom temperature	age-specific geographic distributions of cod evident during autumn in Gulf of St. Lawrence; with increasing age cod become more widely distributed and occur in deeper, colder, more saline water
Campbell & Stasko (1986)	Bay of Fundy/Gulf of Maine	bottom temperature	temperature-dependent, seasonal deep-shallow migration explains both local and long distance migrations of mature lobster
Christie & Regier (1988)	temperate freshwater lakes in North America	temperature	individual species yield of lake trout, whitefish, walleye, northern pike a function of available optimal thermal habitat (i.e. thermal regions that maximize net rate of energy gain); thermal preferenda used to establish area or volume of water that maximizes growth of benthic and pelagic species respecitvely

Table 2. Summary of published studies conducted in Canadian Atlantic waters that examine the influence of physical factors on finfish and shellfish recruitment.

Source	Location	Species	Physical Factor	Comments
Dickie (1955)	Bay of Fundy	scallops	average Sept.-Oct. temperatures at 90 m	high temperatures result in rapid larval development and good survival; such conditions occur when water exchange between Bay of Fundy and the sea outside is minimal leading to larval retention; temperature lagged 6 years; i.e. at the time scallops were recruited into population
Templeman (1965)	southern Grand Bank	haddock	iceberg numbers south of 48° N	7 out of 8 moderately abundant to very abundant year classes of haddock since 1942 occurred in years when low (<100) iceberg numbers occurred
Templeman & Hodder (1965)	southern Grand Bank	haddock	slope-water intrusions of warm water	strongest year class (1955) on record coincided with intrusions of warm slope water onto bank during spawning period
Martin & Kohler (1965)	New England, western Nova Scotia, Gulf of St. Lawrence	cod	SST (annual means)	dominant year classes distributed over contiguous areas; weak year classes associated with above average temperatures and vice versa
Sutcliffe (1972, 1973)	Gulf of St. Lawrence	lobster, halibut, haddock, soft-shell clams	monthly St. Lawrence River discharge (=RIVSUM)	maximum correlations obtained when landings lagged discharge by amount equal to age at maturity; lagged discharge and coastal SSTs strongly correlated

Table 2. (Continued)

Source	Location	Species	Physical Factor	Comments
Sissenwine (1974)	southern New England	yellowtail flounder	air temperature	decline of yellowtail flounder fishery during late 1940s coincided with a warming trend in the region
Lett & Kohler (1976)	Gulf of St. Lawrence	herring	SST	temperature used as input for stochastic model for herring along with predation and competition from mackerel; temperature and abundance of 0-group mackerel affected herring growth rate
Sutcliffe *et al*. (1977), Drinkwater (1987), Drinkwater & Myers (1987)	Gulf of Maine	17 commercial marine species	SST, RIVSUM	negative correlations evident among "cold" water species (eg. cod, redfish, yellowtail) and positive correlations among "warm" water species (eg. butterfish, menhaden); distributional limits determine sign (+ or -) of response
Kudlo & Boytsov (1979)	Flemish Cap	cod	vertical and horizontal water velocities derived from geostrophic circulation charts	75% of recruitment variation explained by intensity of these two variables during egg and larval period; physical quantities derived are difficult to interpret
Sinclair *et al*. (1980)	Scotian Shelf	herring	southwesterly (240°) wind at Sable Island and Halifax at sea level	no plausible mechanism available to explain relationships, rather statistical criteria used to develop model
Skud (1982)	New England and Canadian Maritime Provinces	herring, mackerel	SST	change in abundance of dominant species positively correlated with SST; abundance of subordinate species was negatively correlated with SST due to competition with dominant

Table 2. (Continued)

Source	Location	Species	Physical Factor	Comments
Iles & Sinclair (1982)	Bay of Fundy/Gulf of Maine	herring	area of vertically mixed regions defined fronts as predicted by the Simpson-Hunter stratification parameter ≡ larval retention area	spawning stock size was positively related to size (km^2) of larval retention area
Sutcliffe et al. (1983)	Labrador Shelf and Grand Bank	cod	summer depth averaged salinities to 50 m	low river discharge into Hudson Bay coupled to decreased stratification leading to enhanced vertical mixing and high nutrient levels and strong year classes; opposite effect proposed during high river discharge; salinities for first three years of life were used in model
Harding et al. (1983)	Gulf of Maine	lobster	monthly SST	warm surface water of sufficient duration is essential for completion of larval stages may be mechanism underlying positive correlations between lobster production and lagged SST (see Flowers & Saila 1972; and Dow 1977)
Leggett et al. (1984)	eastern Newfoundland	capelin	onshore wind frequency during July and sum of monthly water temp. for July-Dec. (0-20 m) at Station 27 during larval period	wind conditions influence both timing and physical condition of larvae at emergence; temperature may be operating via its influence on food production

Table 2. (Continued)

Source	Location	Species	Physical Factor	Comments
Koslow (1984), Koslow et al. (1987)	Northwest Atlantic	cod, haddock, redfish, mackerel, herring stocks	large scale physical factors as opposed to biological interactions; large scale patterns of SST and atmospheric pressure, freshwater run off, and offshore winds	consistent positive correlations between stocks of the same species and between guilds of species (eg. demersal, offshore spawning species or inshore, pelagic species); covariability between physical factors and recruitment time series
Winters et al. (1985)	Fortune Bay, Nfld./ Gulf of St. Lawrence	herring	sum of mean monthly SST for 0-20 m at Station 27 6 months prior to spawning (Nov.-April)	recruitment for the 1964-75 year classes was significantly correlated with prespawning temperatures; no correlation with postspawning temperatures or egg production; parallelism in year classes among southern Gulf of St. Lawrence stocks, northeast Newfoundland coast stocks and Fortune Bay
Myers & Drinkwater (1988)	Scotian Shelf, Grand Banks, Labrador Shelf	stocks of cod, haddock, redfish, silver hake, plaice, herring, argentine	Ekman transport	no statistical relationship evident between simulated Ekman transport of eggs and larvae and subsequent recruitment; possibly due to broad shelf off eastern Canada relative to cross-shelf excursions
Myers & Drinkwater (1988)	Northwest Atlantic	stocks of groundfish: cod, pollock, haddock, redfish, yellowtail, silver hake	stock specific annual indices of warm core ring (WCR) activity and shelf-slope front variability	increased WCR activity reduces recruitment in 17 groundfish stocks examined through offshore entrainment of egg and larval stages

Table 3. Sign of the correlation coefficient between recruitment and sea surface temperature in the Gulf of Maine for several commercially important finfish and shellfish species. Results derived from analysis by Sutcliffe et al. 1977.

+	-
alewife	soft clams
butterfish	cod
hard clams	cusk
silver hake	haddock
red hake	Atlantic halibut
herring	redfish
menhaden	striped bass
scallops	yellowtail flounder

Table 4. Examples from field and laboratory studies of influences of physical factors on finfish and shellfish physiology (i.e. growth, maturation, fecundity, and mortality).

Source	Location	Species	Physical Factor	Physiological Response
McLeese & Wilder (1958)	St. Andrews, N.B.	lobster	bottom water temperature	increased temperatures caused increased activity (i.e. walking rate) and catchability over 2° to 10° C
May _et el_. (1965)	Newfoundland area	cod	water temperature	growth parameters K and L_∞ related to latitude; highest K and lowest L_∞ occurred in cooler waters of higher latitude while reverse was true for warmer water to the south
Hodder (1965)	Grand Bank	haddock	January to May water temperature at Station 27	year-to-year variation in fecundity explained, in part, by temperature
Sinderman (1965)	western North Atlantic	herring	summer sea temperature	intensity of parasitization by the larval trematode _Cryptocotyle_ and the myxosporidian _Kudoa_ associated with coastal areas exceeding 15° C in summer
Lauzier & Tibbo (1965) Messieh (1986)	southern Gulf of St. Lawrence	herring	April sea surface temperature, ice conditions	determines average arrival time on spawning grounds; low temperatures delay spawning and vice versa
Marak & Livingston (1970)	Georges Bank	haddock	March-April bottom temperature	1.5-2° C temperature change produced a difference in spawning time by one month; spawning time earlier and spawning duration prolonged in warm years and vice versa

Table 4. (Continued)

Source	Location	Species	Physical Factor	Physiological Response
Jeffries & Johnson (1974)	Narragansett Bay, R.I.	winter flounder	water temperature	interannual variation in the intensity of spring migration measured as CPUE in May directly related to water temperature in April
Laurence & Rogers (1976)	lab study of eggs from cod and haddock from Narragansett Bay	cod, haddock	temperature, salinity	egg mortality, hatching time, and size at hatch evaluated under 36 different combinations of temperature and salinity; cod embryos more eurythermal and euryhaline than haddock
Pauly (1980)	Northwest Atlantic	cod, haddock, plaice, yellowtail, winter flounder	water temperature	derived multiple linear regressions for estimating natural mortality (M) of population from mean annual water temperature and parameters of VonBertalanffy growth equation (L, W_{∞}, K); temperature posititely correlated with M
Garcia (1981) Showell & Waldron (1986)	Scotian Shelf	silver hake	water temperature	timing of spawning migration influenced by rate of warming of the shelf waters shoreward of the ∿100 m isobath
Grimm (1983)	Georges Bank	herring	bottom temperature	delayed spawning and shorter spawning duration associated with a warming trend commencing in 1971
Holdway & Beamish (1984)	lab study of cod from Passamaguoddy Bay, N.B.	cod	water temperature of 5° and 8° C	relative energy, protein, and lipid levels of whole cod decreased with increasing temperature; muscle tissue contained higher relative lipid levels at 5° C; higher basal metabolism and lower activity levels at 8° C

Table 4. (Continued)

Source	Location	Species	Physical Factor	Physiological Response
Scheibling & Stephenson (1984)	Nova Scotia coast	indirect effect on lobster	cumulative sea surface temperature during August to November exceeding 12° C	mass mortality of sea urchins, which are capable of destroying the preferred seaweed habitat of lobsters, occurs when immunity breaks down to water borne disease at high temperatures

Table 5. Groundfish stocks that Myers and Drinkwater (1988) have identified as being negatively affected by warm core ring (WCR) activity. Consequently, the anticipated reduction in warm core ring activity associated with a doubling of atmospheric CO_2 should result in less frequent episodes of poor recruitment among these stock.

Species	Stock
Cod	3NO 3Ps 4VWs 4X
Pollock	4VWX+5
Haddock	3NO 3Ps 4VW 4X 5Xe
Redfish	3O 3P 4VWX 5YZ
Silver hake	4VWX 5Ze

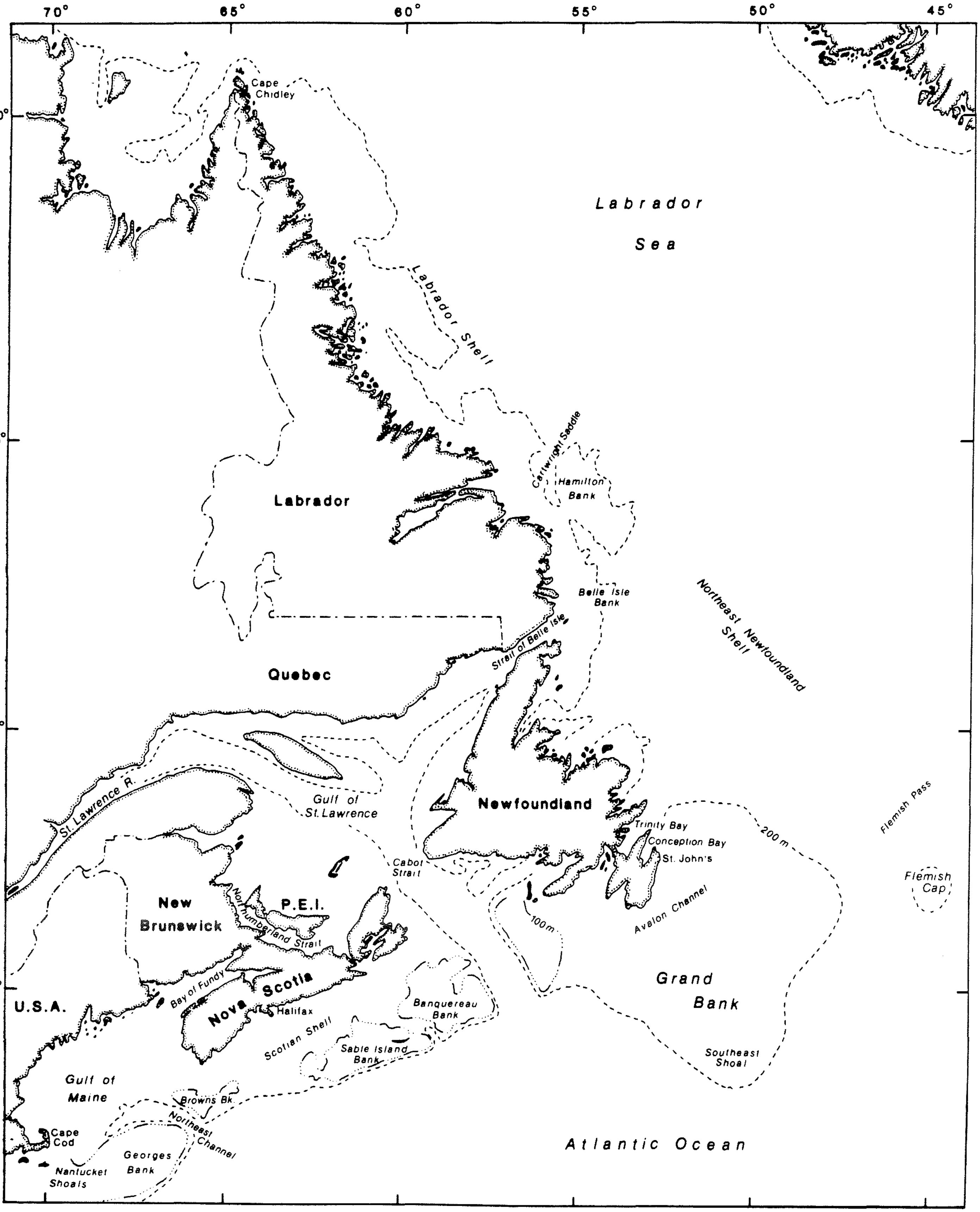

70°
65°
60°
55°
50°
45°
60°
55°
50°
45°
Cape Chidley
Labrador
Sea
Labrador Shelf
Cartwright Saddle
Hamilton Bank
Labrador
Belle Isle Bank
Northeast Newfoundland Shelf
Strait of Belle Isle
Quebec
St. Lawrence R.
Gulf of St. Lawrence
Newfoundland
Flemish Pass
Trinity Bay
Conception Bay
St. John's
200 m
Flemish Cap
Cabot Strait
New Brunswick
P.E.I.
Northumberland Strait
100 m
Avalon Channel
Grand Bank
Bay of Fundy
Nova Scotia
Halifax
Banquereau Bank
U.S.A.
Scotian Shelf
Sable Island Bank
Southeast Shoal
Gulf of Maine
Browns Bk
Northeast Channel
Cape Cod
Georges Bank
Nantucket Shoals
Atlantic Ocean

Figure 1.

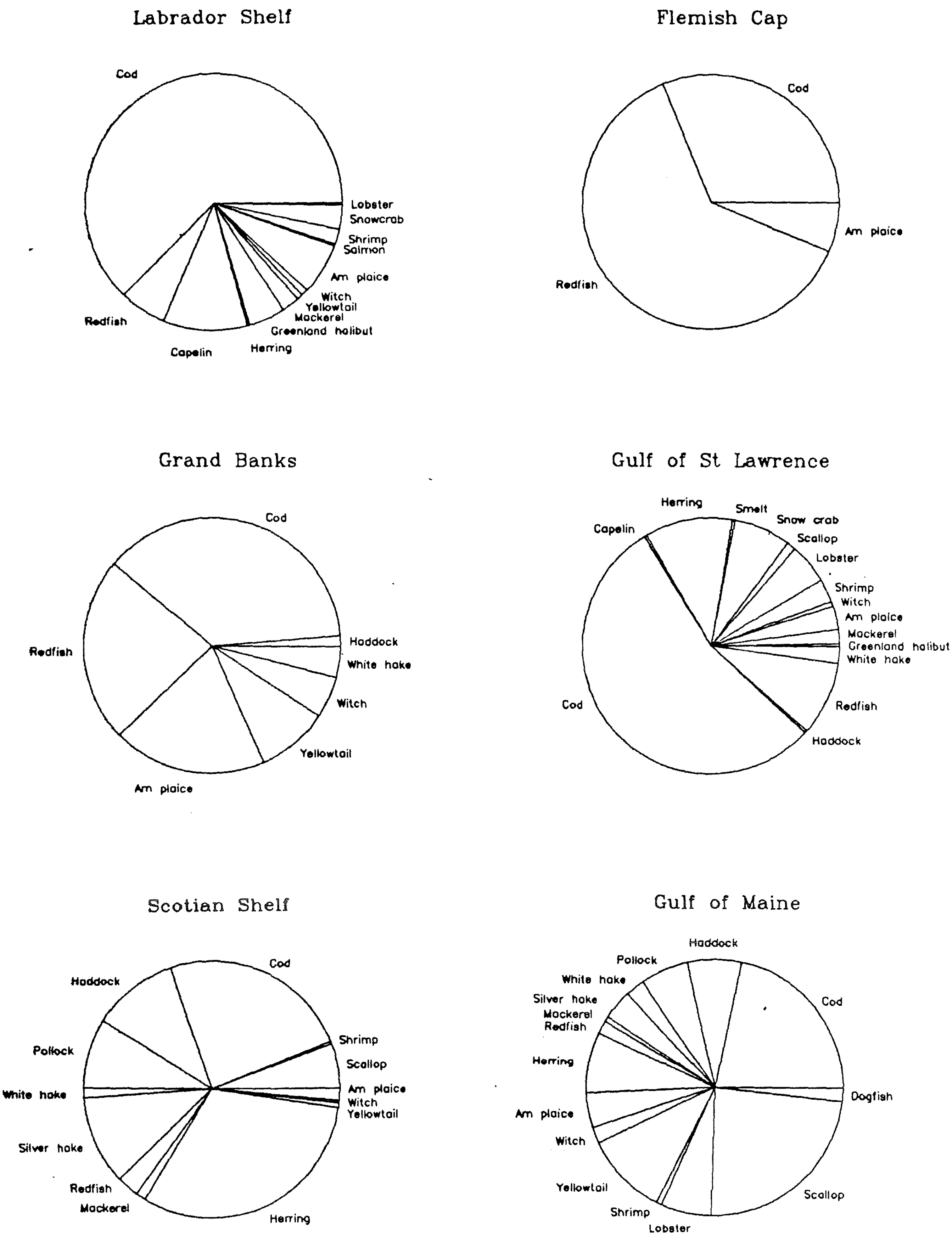

Labrador Shelf
Cod
Lobster
Snowcrab
Shrimp
Salmon
Am plaice
Witch
Yellowtail
Mackerel
Greenland halibut
Herring
Capelin
Redfish
Flemish Cap
Cod
Am plaice
Redfish
Grand Banks
Cod
Haddock
White hake
Witch
Yellowtail
Am plaice
Redfish
Gulf of St Lawrence
Herring
Smelt
Snow crab
Scallop
Lobster
Shrimp
Witch
Am plaice
Mackerel
Greenland halibut
White hake
Redfish
Haddock
Cod
Capelin
Scotian Shelf
Cod
Shrimp
Scallop
Am plaice
Witch
Yellowtail
Herring
Mackerel
Redfish
Silver hake
White hake
Pollock
Haddock
Gulf of Maine
Haddock
Cod
Dogfish
Scallop
Lobster
Shrimp
Yellowtail
Witch
Am plaice
Herring
Silver hake
Mackerel
Redfish
White hake
Pollock

Figure 2.

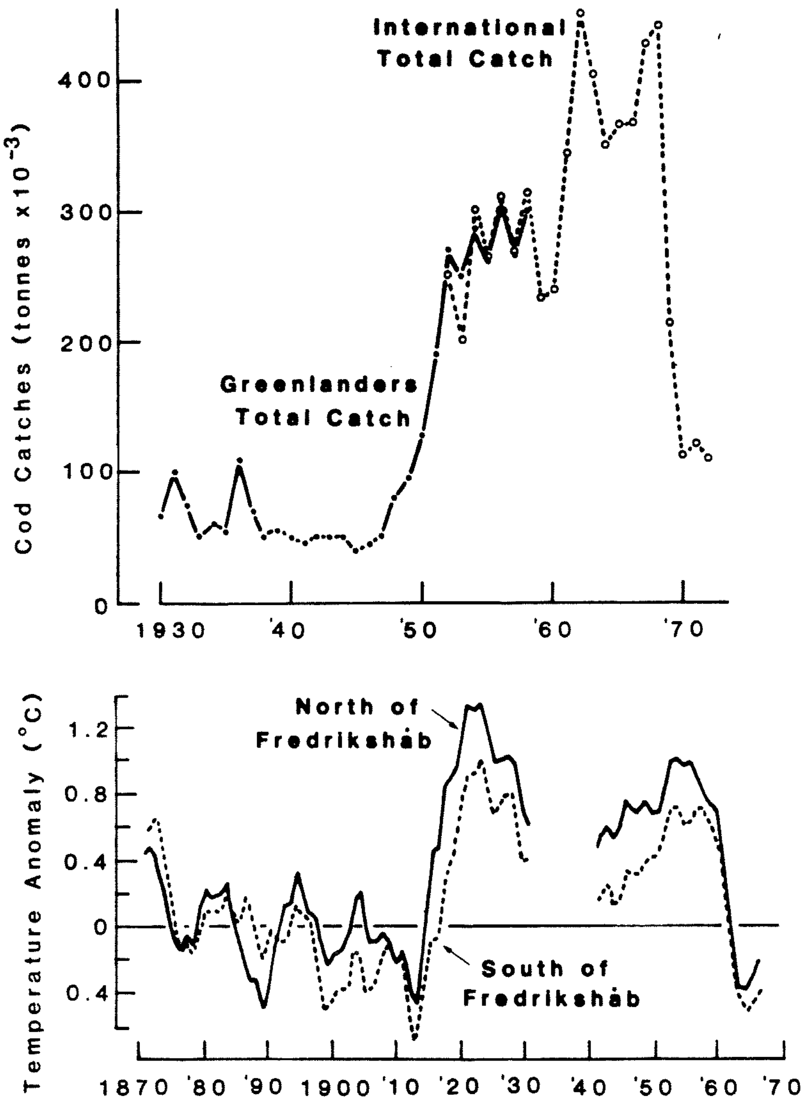

International
Total Catch
Greenlanders
Total Catch
Cod Catches (tonnes x10⁻³)
0
100
200
300
400
1930
'40
'50
'60
'70
North of
Fredrikshåb
South of
Fredrikshåb
Temperature Anomaly (°C)
1.2
0.8
0.4
0
0.4
1870
'80
'90
1900
'10
'20
'30
'40
'50
'60
'70

Figure 3.

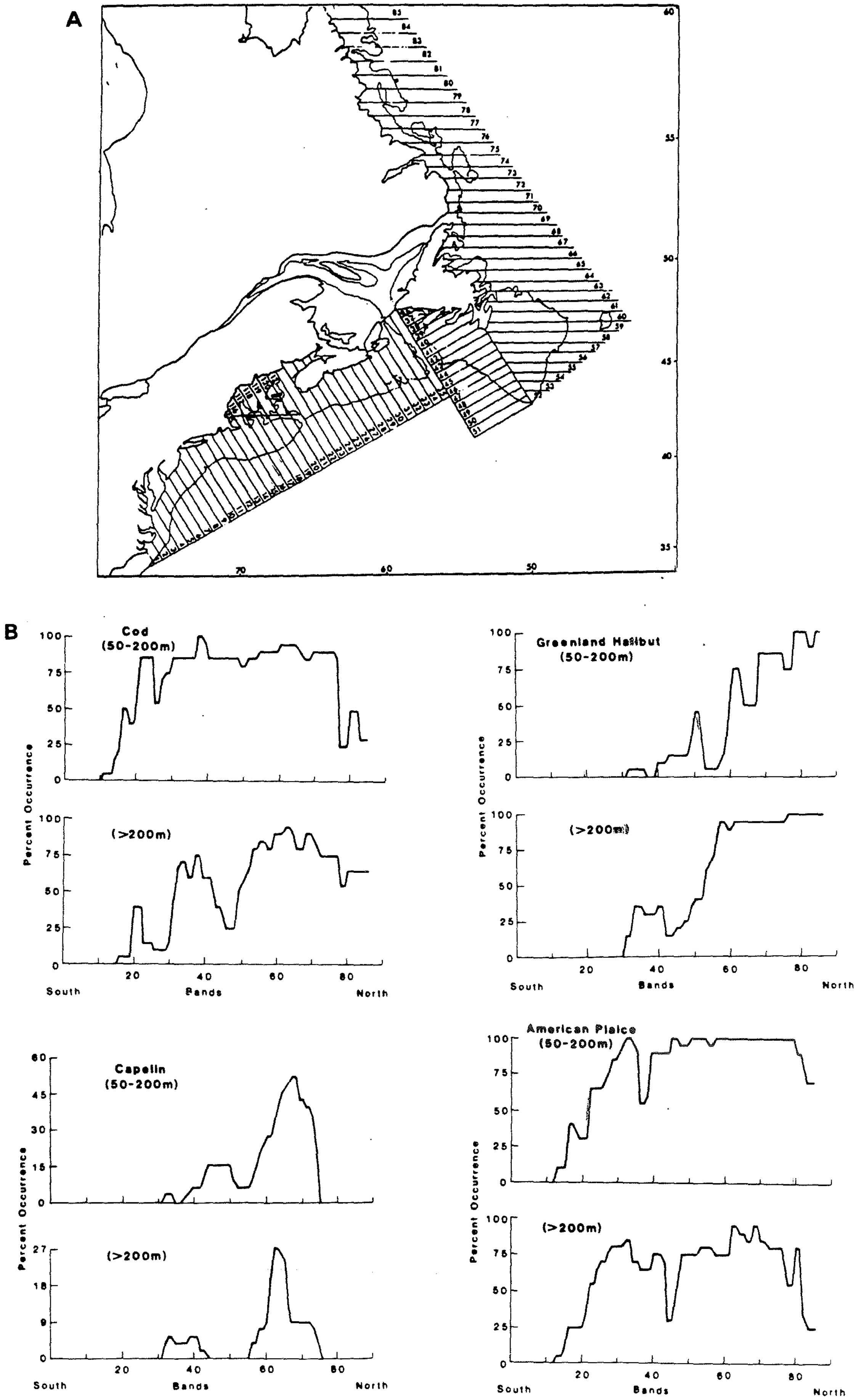

A
B
Cod
(50-200m)
(>200m)
Greenland Halibut
(50-200m)
(>200m)
Capelin
(50-200m)
(>200m)
American Plaice
(50-200m)
(>200m)
Percent Occurrence
South
Bands
North

Figure 4.

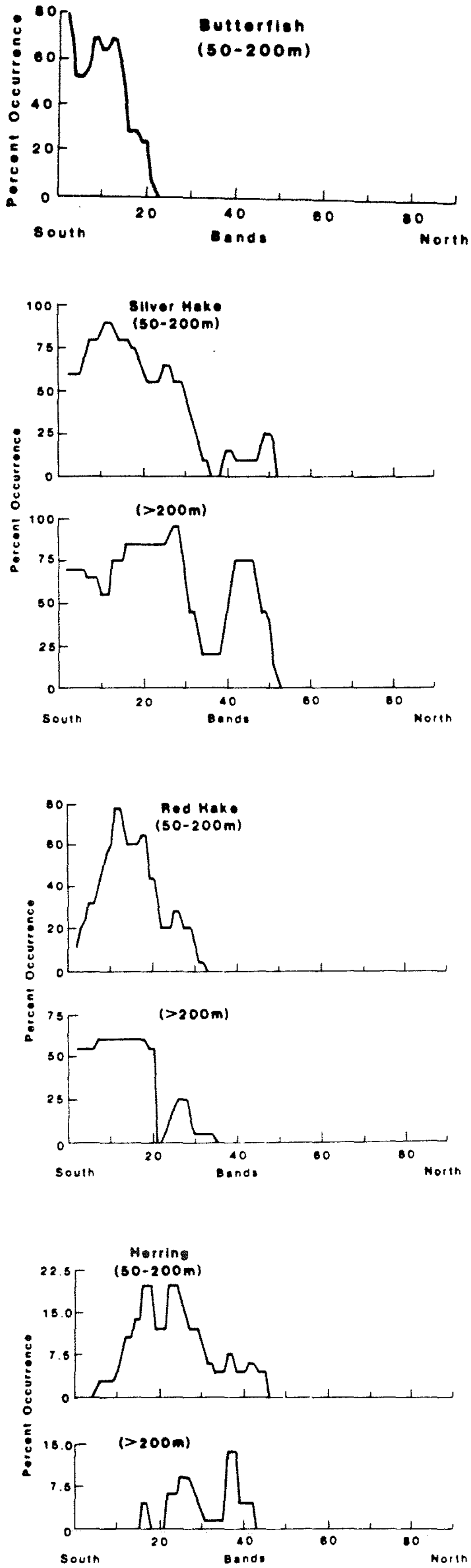

Butterfish
(50-200m)
Percent Occurrence
80
60
40
20
0
20
40
60
80
South
Bands
North
Silver Hake
(50-200m)
(>200m)
Percent Occurrence
100
75
50
25
0
20
40
60
80
South
Bands
North
Red Hake
(50-200m)
(>200m)
Percent Occurrence
80
60
40
20
0
75
50
25
0
20
40
60
80
South
Bands
North
Herring
(50-200m)
(>200m)
Percent Occurrence
22.5
15.0
7.5
0
15.0
7.5
0
20
40
60
80
South
Bands
North

Figure 5.

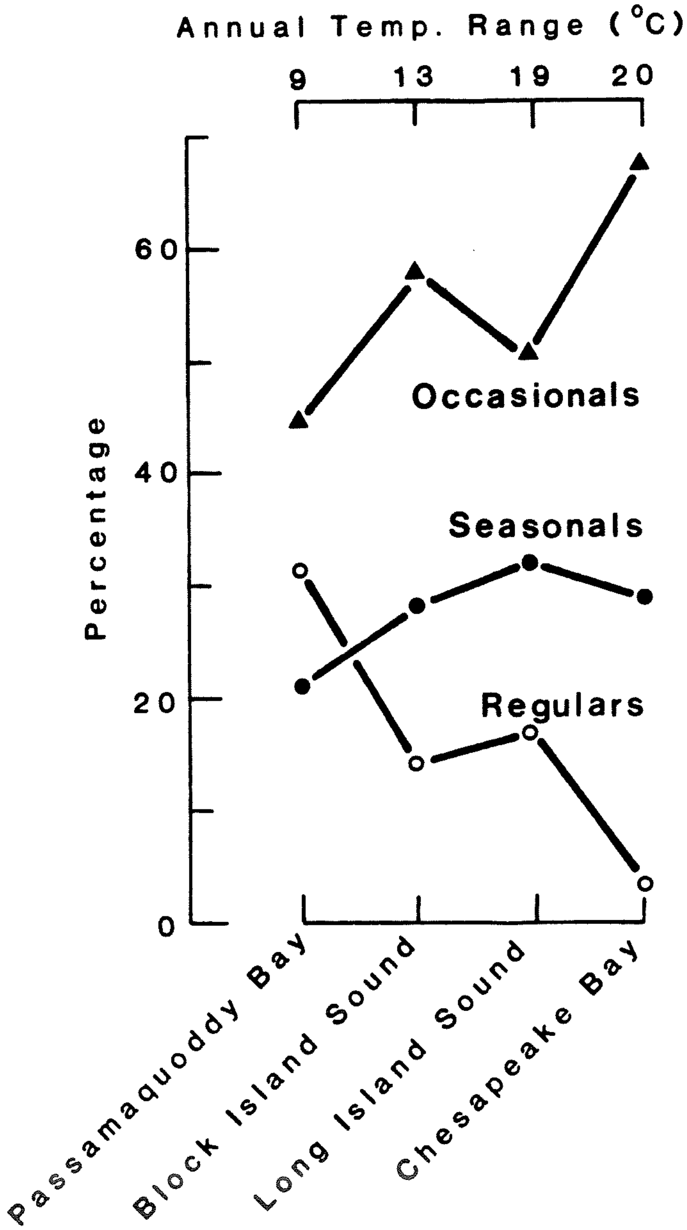

Annual Temp. Range (°C)
9
13
19
20
60
40
20
0
Percentage
Occasionals
Seasonals
Regulars
Passamaquoddy Bay
Block Island Sound
Long Island Sound
Chesapeake Bay

Figure 6.

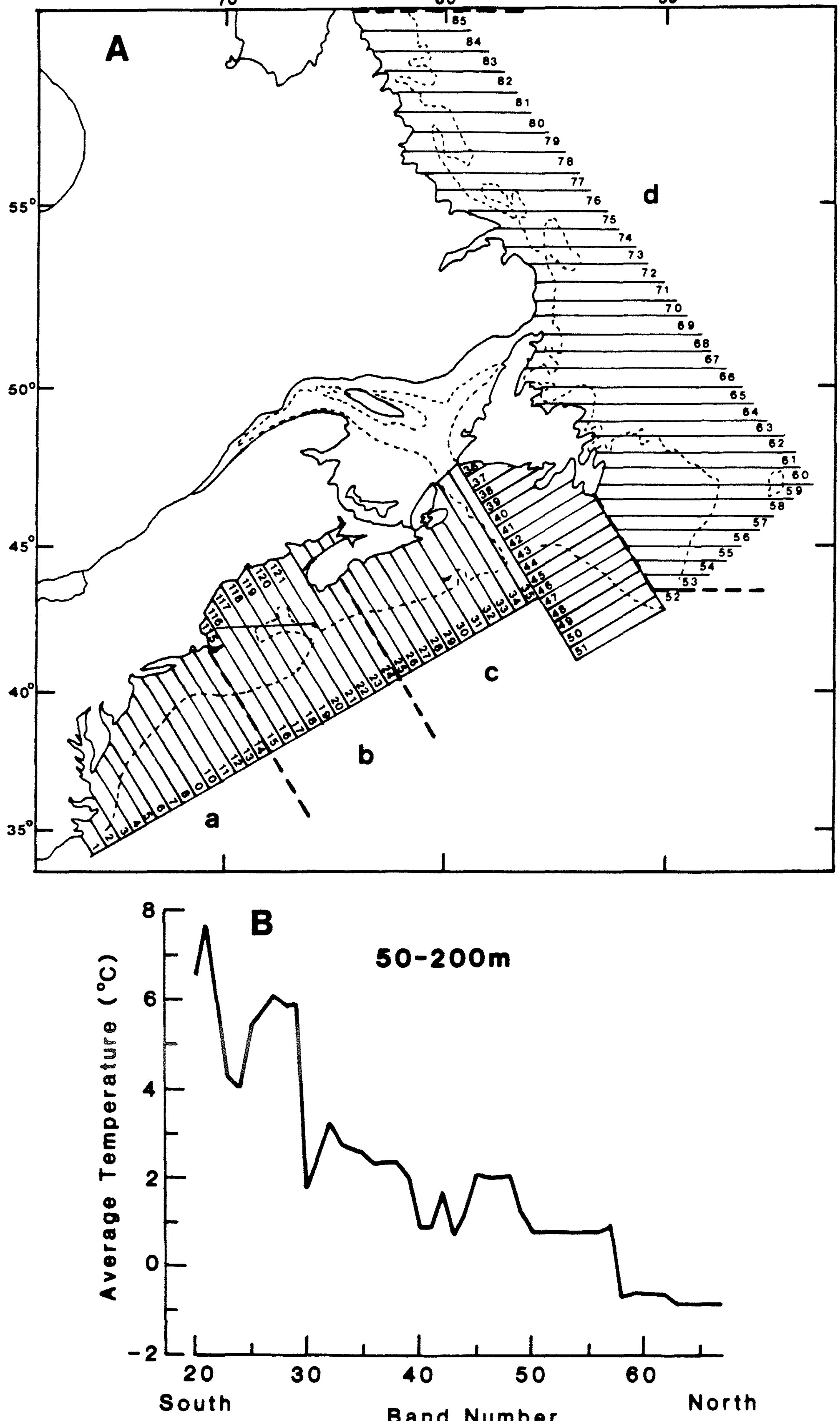
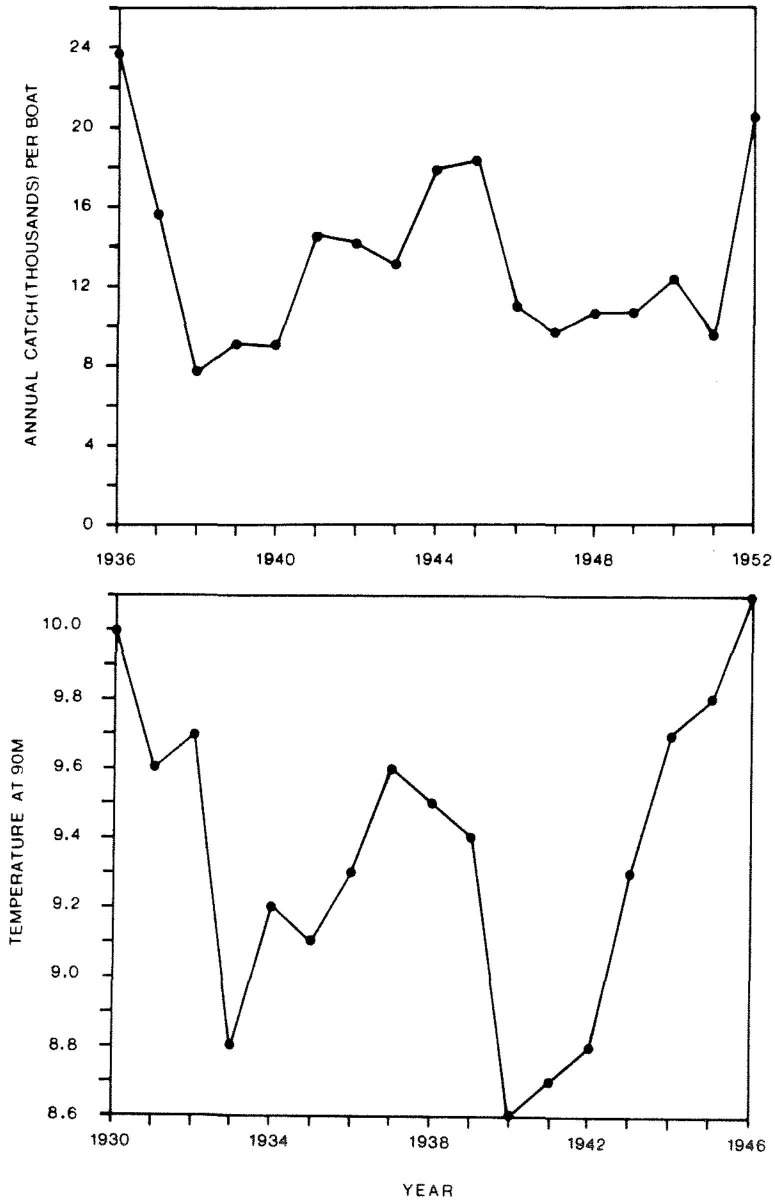

A
70°
60°
50°
55°
50°
45°
40°
35°
a
b
c
d
B
50-200m
Average Temperature (°C)
8
6
4
2
0
-2
20
30
40
50
60
South
Band Number
North

Figure 7.



ANNUAL CATCH(THOUSANDS) PER BOAT
24
20
16
12
8
4
0
1936
1940
1944
1948
1952
TEMPERATURE AT 90M
10.0
9.8
9.6
9.4
9.2
9.0
8.8
8.6
1930
1934
1938
1942
1946
YEAR

Figure 8.

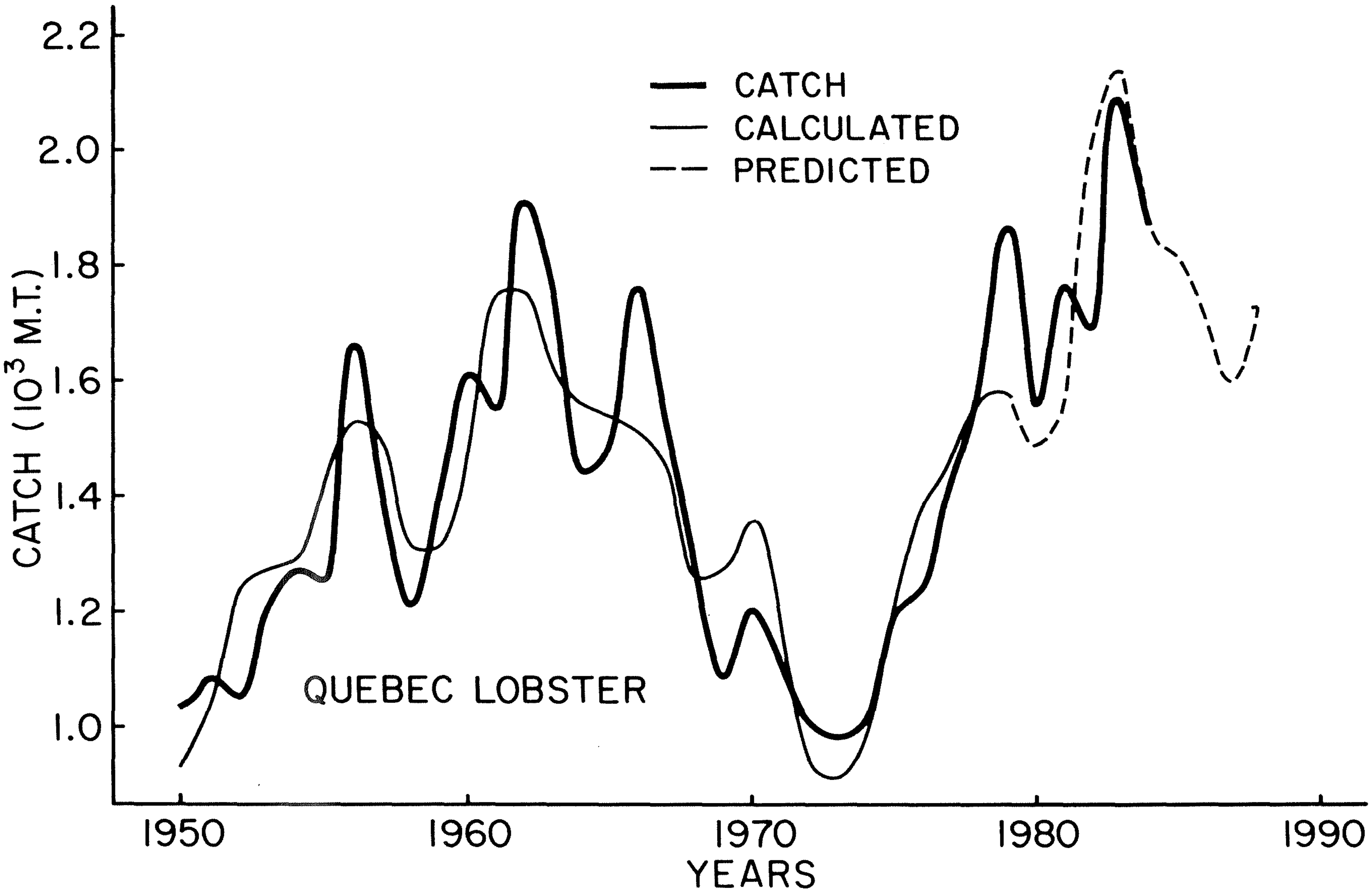

CATCH
CALCULATED
PREDICTED
QUEBEC LOBSTER
CATCH (10^3 M.T.)
2.2
2.0
1.8
1.6
1.4
1.2
1.0
1950
1960
1970
1980
1990
YEARS

Figure 9.

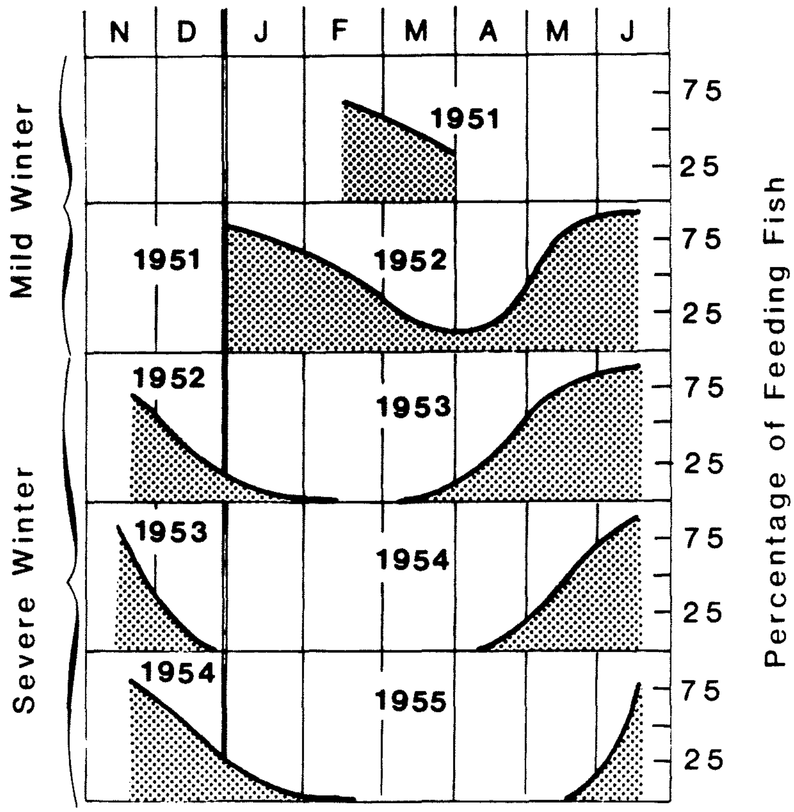

N
D
J
F
M
A
M
J
Mild Winter
Severe Winter
1951
1951
1952
1952
1953
1953
1954
1954
1955
75
25
Percentage of Feeding Fish

Figure 10.

Percentage demersal fish =

$$100 \exp -(0.12\,T)$$

where T = bottom water temperature

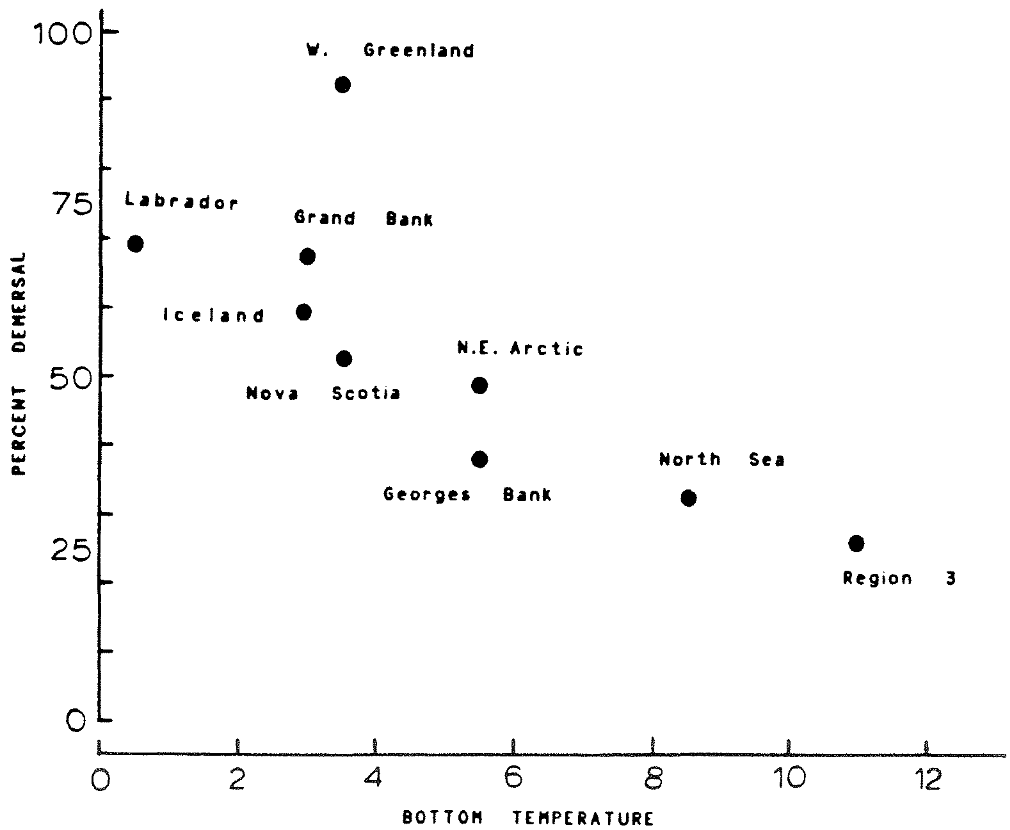


Figure 11.

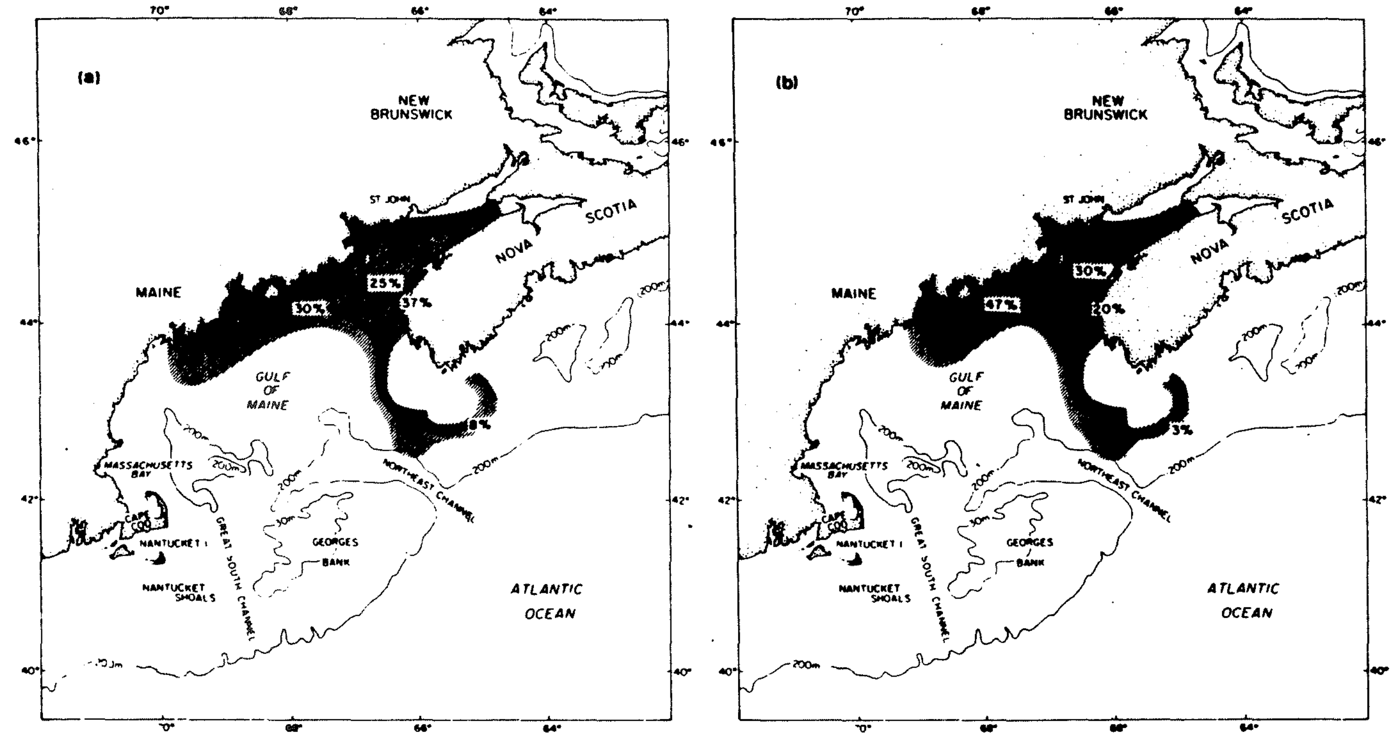
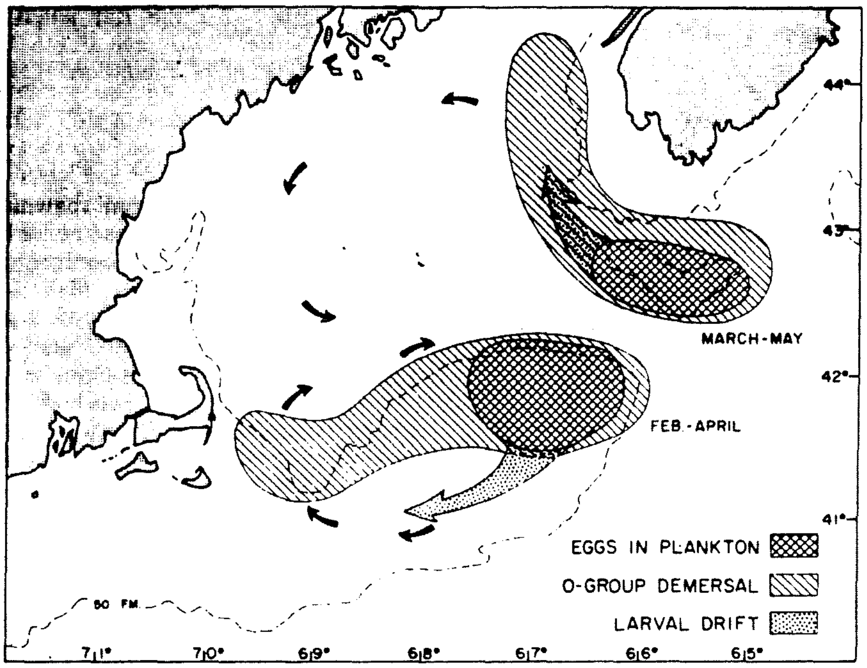

(a)
NEW BRUNSWICK
ST JOHN
NOVA SCOTIA
MAINE
30%
25%
37%
8%
GULF OF MAINE
MASSACHUSETTS BAY
CAPE COD
NANTUCKET I
NANTUCKET SHOALS
GREAT SOUTH CHANNEL
GEORGES BANK
NORTHEAST CHANNEL
ATLANTIC OCEAN
200m
(b)
NEW BRUNSWICK
ST JOHN
NOVA SCOTIA
MAINE
47%
30%
20%
3%
GULF OF MAINE
MASSACHUSETTS BAY
CAPE COD
NANTUCKET I
NANTUCKET SHOALS
GREAT SOUTH CHANNEL
GEORGES BANK
NORTHEAST CHANNEL
ATLANTIC OCEAN
200m
70°
68°
66°
64°
46°
44°
42°
40°

Figure 12.


44°
43°
42°
41°
MARCH-MAY
FEB.-APRIL
EGGS IN PLANKTON
O-GROUP DEMERSAL
LARVAL DRIFT
50 FM.
71°
70°
69°
68°
67°
66°
65°

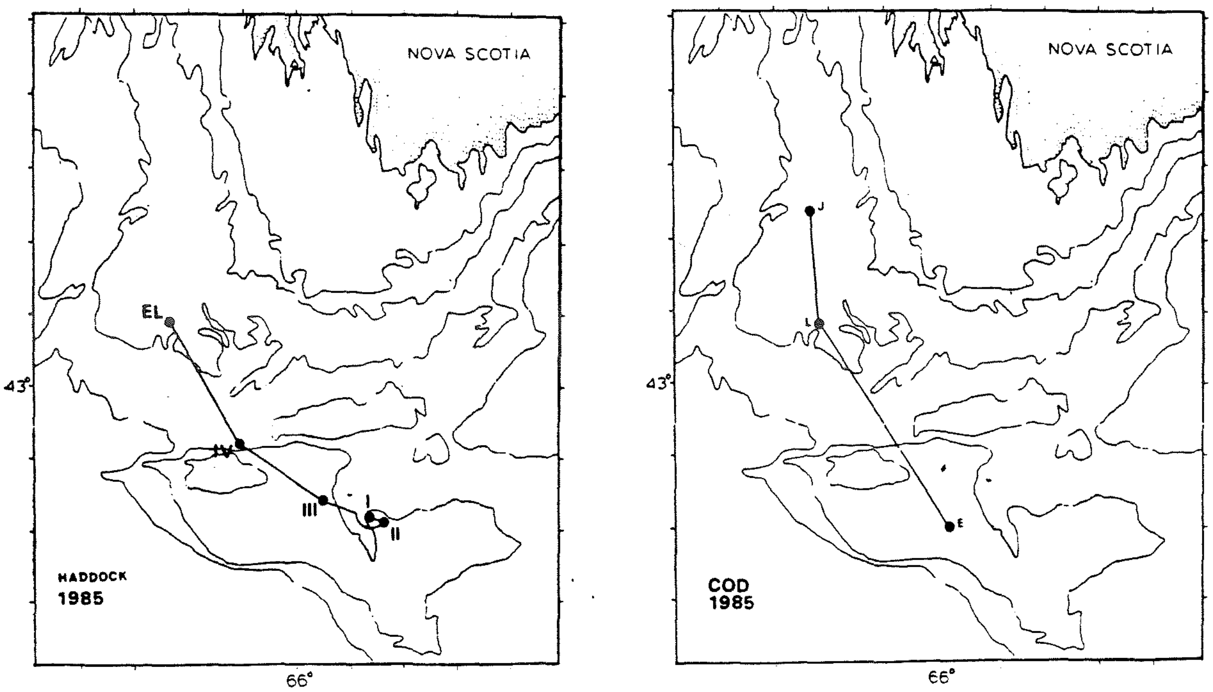

NOVA SCOTIA
EL
IV
III
I
II
HADDOCK
1985
43°
66°
NOVA SCOTIA
J
L
E
COD
1985
43°
66°

Figure 13.

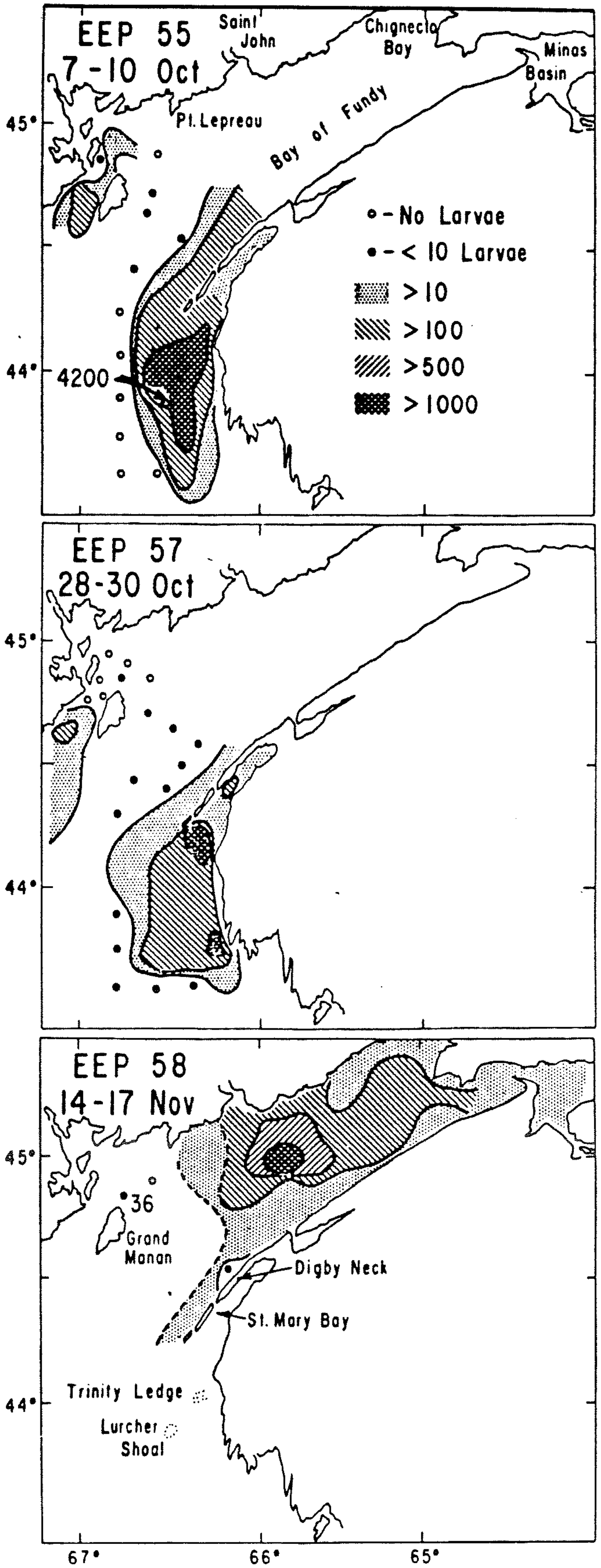

EEP 55
7-10 Oct
Saint John
Chignecto Bay
Minas Basin
Pt. Lepreau
Bay of Fundy
o - No Larvae
• - < 10 Larvae
>10
>100
>500
>1000
4200
45°
44°
EEP 57
28-30 Oct
45°
44°
EEP 58
14-17 Nov
36
Grand Manan
Digby Neck
St. Mary Bay
Trinity Ledge
Lurcher Shoal
45°
44°
67°
66°
65°

Figure 14.

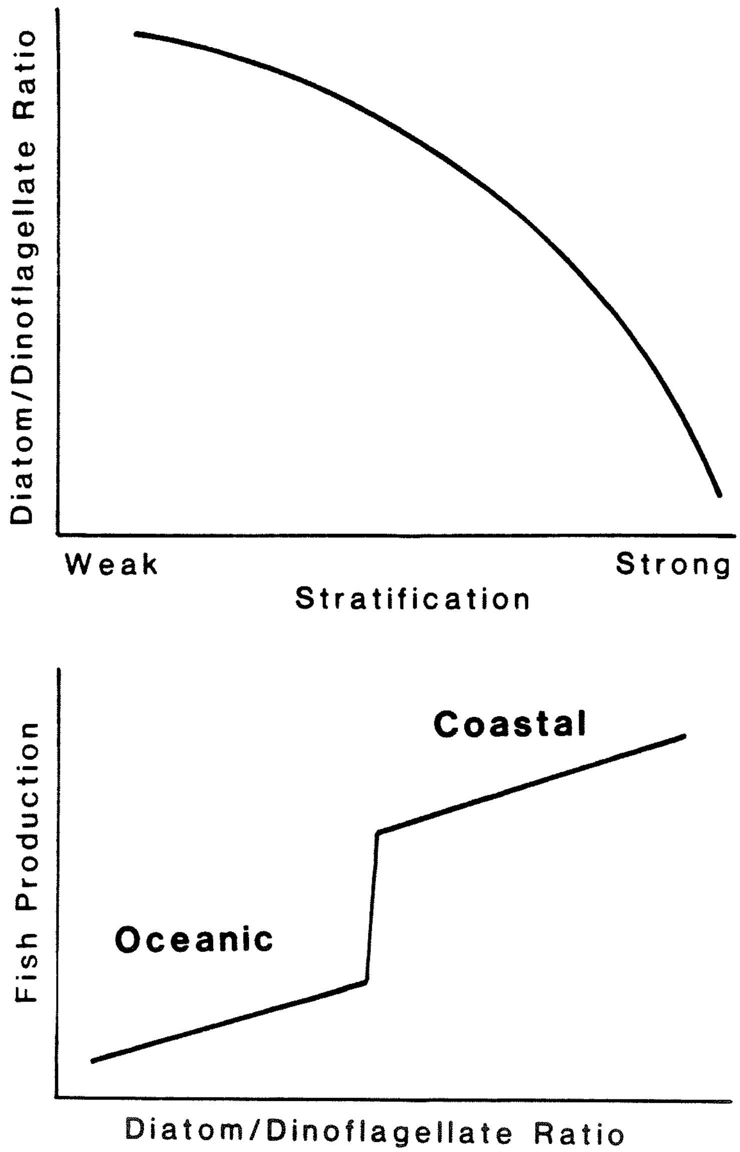

Diatom/Dinoflagellate Ratio
Weak
Strong
Stratification
Fish Production
Coastal
Oceanic
Diatom/Dinoflagellate Ratio

Figure 15.

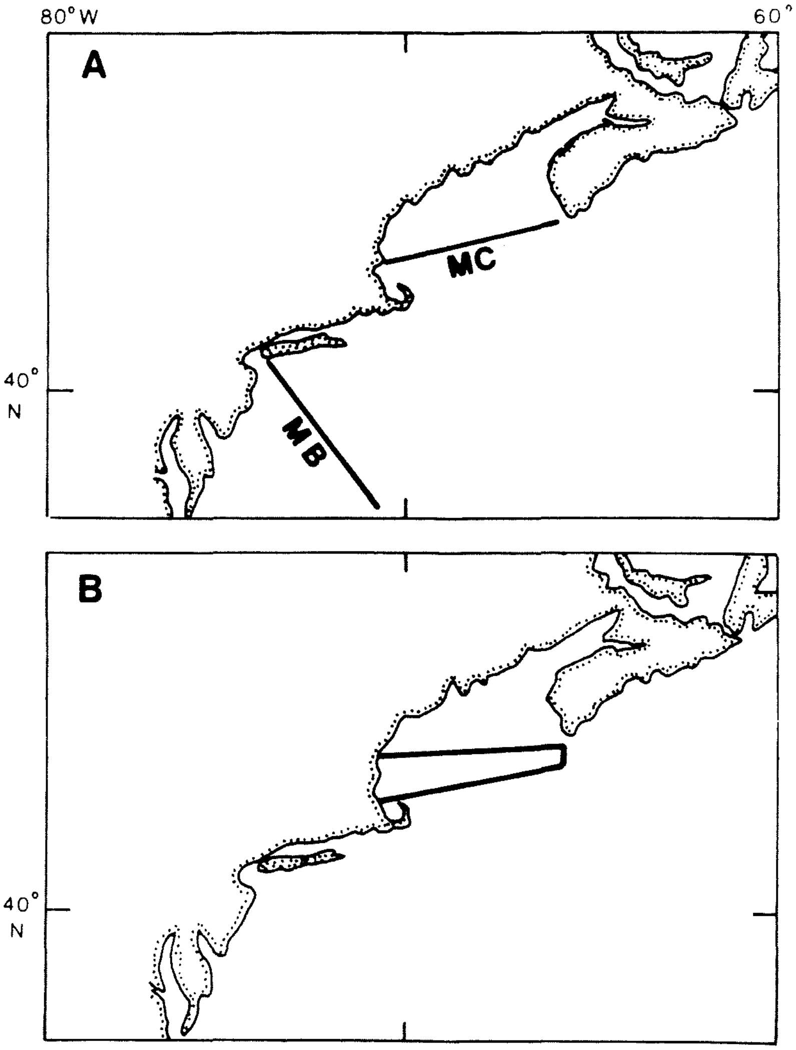


Figure 16.

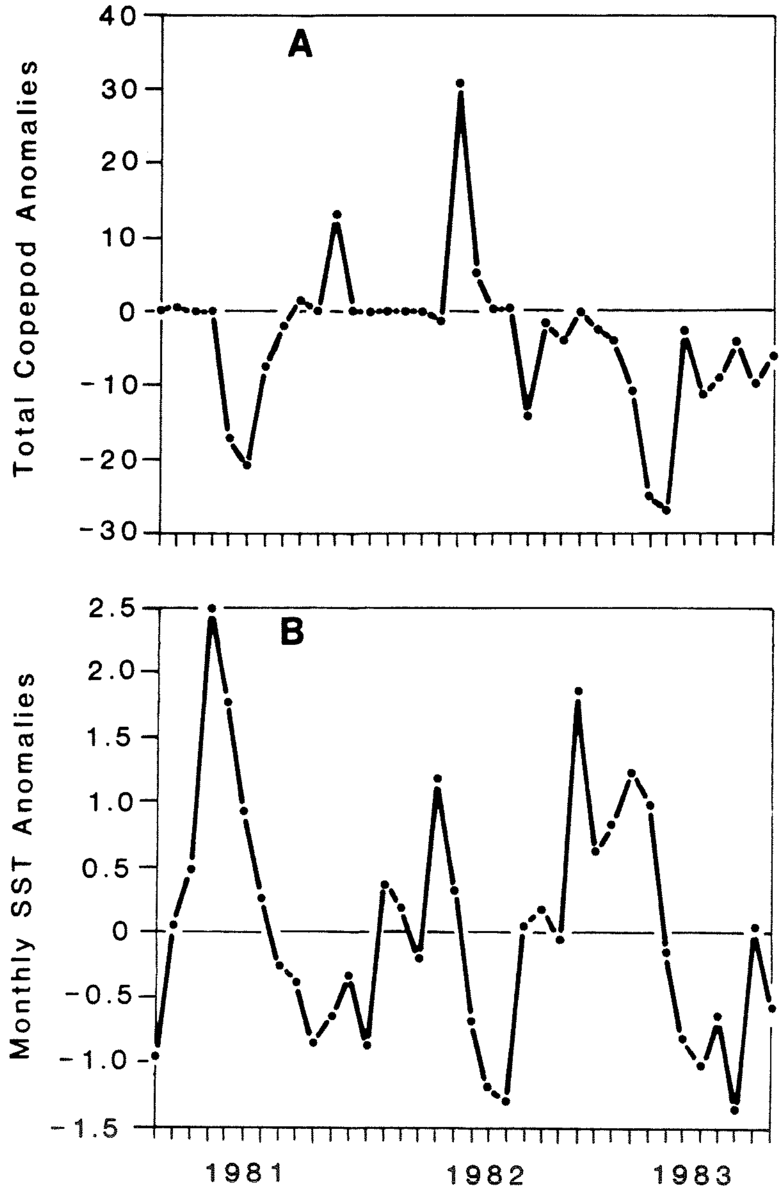

A
B
Total Copepod Anomalies
Monthly SST Anomalies
40
30
20
10
0
-10
-20
-30
2.5
2.0
1.5
1.0
0.5
0
-0.5
-1.0
-1.5
1981
1982
1983

Figure 17.

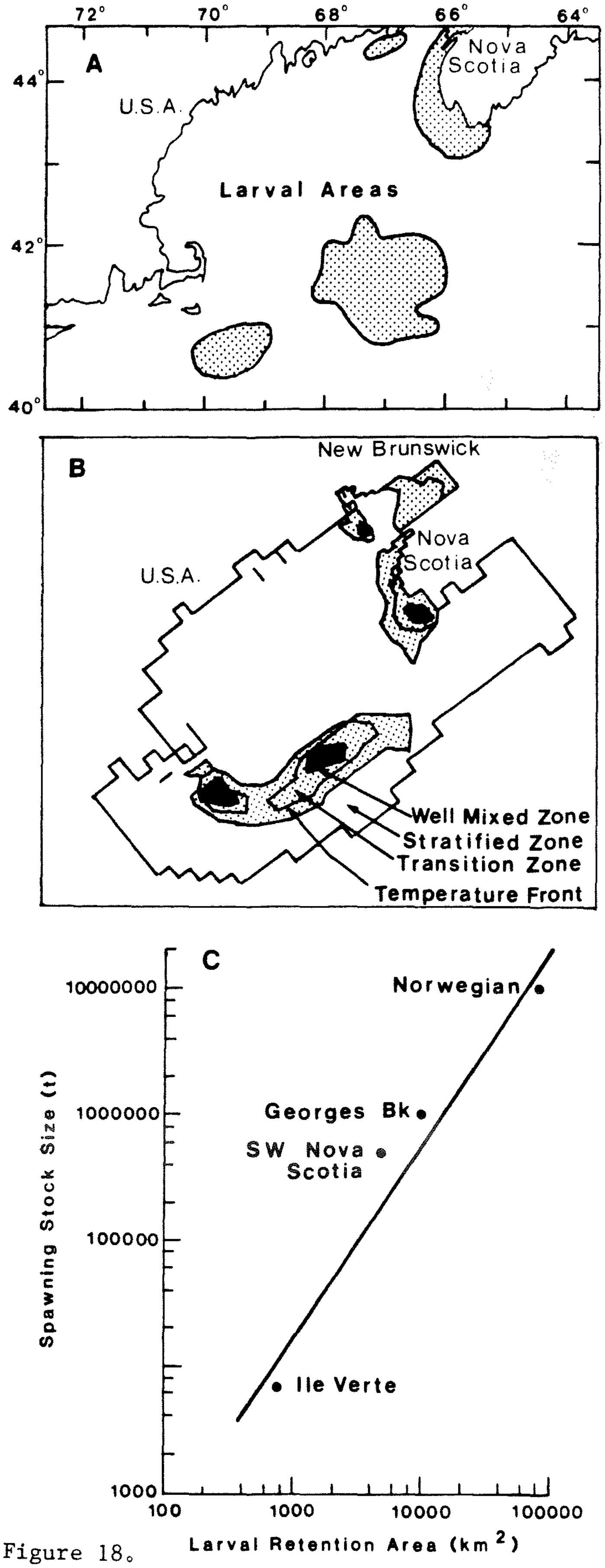
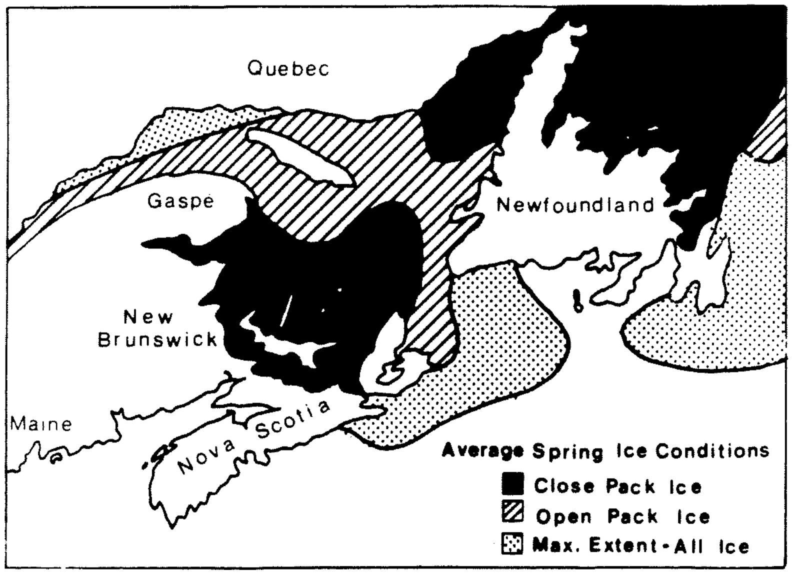

72°
70°
68°
66°
64°
44°
42°
40°
A
U.S.A.
Nova Scotia
Larval Areas
B
New Brunswick
U.S.A.
Nova Scotia
Well Mixed Zone
Stratified Zone
Transition Zone
Temperature Front
C
Norwegian
Georges Bk
SW Nova Scotia
Ile Verte
10000000
1000000
100000
1000
100
1000
10000
100000
Spawning Stock Size (t)
Larval Retention Area (km 2)

Figure 18.


Quebec
Gaspe
Newfoundland
New Brunswick
Maine
Nova Scotia
Average Spring Ice Conditions
Close Pack Ice
Open Pack Ice
Max. Extent-All Ice

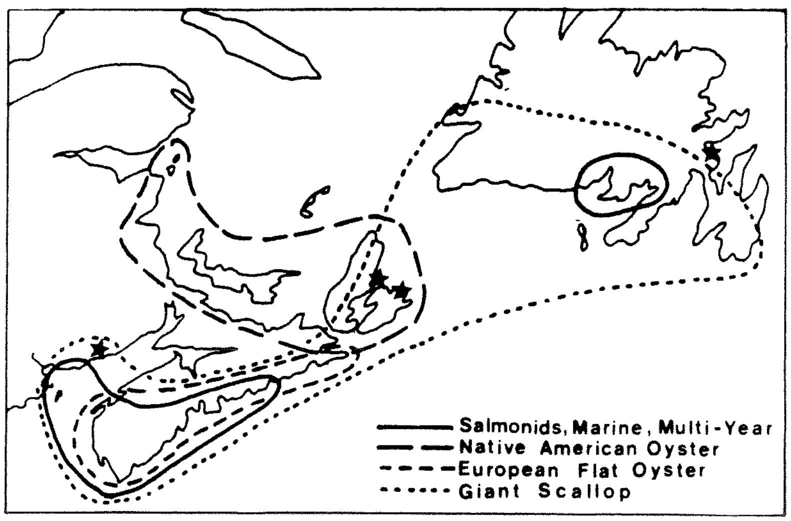

Salmonids, Marine, Multi-Year
Native American Oyster
European Flat Oyster
Giant Scallop

Figure 19.