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Spatial analysis of northern Atlantic cod distribution with respect to bottom temperature and estimation of biomass using potential mapping in SPANS

by

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Abstract

The spatial analysis technique (referred to as SPANdex) used in this study to estimate biomass converts point estimates, in this case individual fall survey set catch rates, into continuous surfaces (density subareas) that perform as survey strata. The strata vary over time taking into account stock distributional shifts. This and the increased number of sets per stratum result in lower within strata variability. Analysis of spatial patterns of distribution and density of cod using the potential mapping technique shows that cod in NAFO Divs. 2J, 3K and 3L has undergone several major changes during the 1980's and 1990's. During the fall in the early 1980's, the cod were found to be aggregated into four areas: North, along the Labrador coast from about Lat. 51^0 to the shelf edge north of Lat. 54^0 30'; Middle, along the shelf edge between Lat. 51^0 30' and Lat. 53^0; South, along the northeast slope of the Grand Bank to Lat. 50^0 30' and; Grand Bank, on the top of the bank at the border of NAFO Div. 3L and 3NO. Among years, how far along the migration of the cod from the inshore to the shelf edge was during the survey affected how far inshore these concentrations extended. After 1985, this pattern started to change as the North concentration started to diminish. It was the largest concentration from 1983 to 1988 and was the first to disappear from the Labrador Shelf during the collapse of the stock. At the same time, the Middle and South (Labrador Shelf) concentrations first increased in terms of extent of high density areas and biomass, then rapidly declined until 1993 where only a small remnant of the South concentration remained. During 1989 to 1991, the remaining cod hyper-aggregated in the South area. In the area along the Labrador coast where the bottom temperature was more variable among years, the cod distribution appeared to vary somewhat independently with respect to temperature. There was no downturn in the fall bottom temperatures during the period of decline. Bottom temperature appeared not to change the behaviour of the migrating cod or directly drive the decline of the stock. On the other hand, the pattern of disappearance of the concentrations (north to south) with respect to the pattern of fishing offshore (not north to south) suggests that fishing pressure was also not the primary cause of the decline.

Résumé

La technique d'analyse spatiale (SPANdex) utilisée dans la présente étude pour estimer la biomasse permet de convertir des estimations ponctuelles, dans ce cas-ci des taux de capture par trait de chalut du relevé d'automne, en des surfaces continues (sous-zones de densité) qui se comportent comme une strate de relevé. La strate varie avec le temps et tient compte de la dérive de la distribution du stock. Cette approche utilisée de pair avec un nombre accru de traits par strate donne lieu à une baisse de la variabilité au sein d'une même strate. L'analyse des allures spatiales de la distribution et de la densité des morues à l'aide de la technique de cartographie potentielle montre que la morue des divisions 2J, 3K et 3L de l'OPANO a subi plusieurs modifications importantes au cours des années 1980 et 1990. À l'automne, au cours du début des années 1980, les morues étaient concentrées dans quatre zones : au nord, le long de la côte du Labrador à partir de 51° de latitude jusqu'au bord du plateau, au nord de 54° 30' de latitude; au centre, le long de la bordure du plateau entre 51° 30' et 53° de latitude; au sud, le long de la pente nord-est du Grand Banc jusqu'à 50°30' de latitude; et le Grand Banc, à son sommet, à la limite entre la division 3L et les divisions 3NO de l'OPANO. Au cours des années, l'importance de la migration des morues de la zone côtière vers la bordure du plateau pendant le relevé influait sur la proximité à la côte des concentrations. Après 1985, ce régime a commencé à se modifier avec la diminution de la concentration nord. Cette concentration était la plus importante entre 1983 et 1988 et a été la première à disparaître du plateau du Labrador au moment de l'effondrement du stock. Au même moment, les concentrations du centre et du sud (plateau du Labrador) ont tout d'abord augmenté et vu leur densité et leur biomasse s'élever pour ensuite s'appauvrir rapidement jusqu'en 1993 où l'on ne retrouvait plus que des vestiges de la concentration du sud. De 1989 à 1991, le reste des morues s'est surconcentré dans la zone sud. Le long de la côte du Labrador, où la température du fond était plus variable d'une année à l'autre, la répartition des morues semble avoir varié de façon assez indépendante de la température. Il n'y a pas eu de baisse de la température du fond à l'automne pendant la période de déclin. La température du fond ne semble pas avoir influé sur les morues en migration ou avoir directement provoqué le déclin du stock. Par ailleurs, l'allure de la disparition des concentrations (du nord au sud) par rapport à l'allure de la pêche hauturière (non du nord vers le sud) porte à croire que la contrainte exercée par la pêche n'était pas non plus la principale cause du déclin.

Introduction

Distribution studies of exploited marine species and in particular northern cod, have often employed either illustrative methods such as expanding symbol or point plots (i.e. Hutchings (1996), Shelton *et al.* (1996), Lilly (1994) but this approach is limited with respect to analysing spatial changes. Statistical analyses based on latitudinal changes such as those done by Rose *et al.* (1994) also do not account for 2 dimensional (east-west as well as north-south) changes in spatial variation. Fish distributions often change in much more complex patterns than along lines of latitude.

Warren (1997) separated autocorrelation in the survey data into spatial and temporal components and Hutchings (1996) looked at trends in average density but only in terms of the stock area as a whole. Atkinson *et al.* (1997) did examine the data spatially, looking at abundance in relation to extent of area occupied by the stock. However, none of these studies looked at the patterns of shifting fish concentrations over the extent of the stock. These are the types of changes in the spatial structure of a population that may occur as the stock destabilizes and begins to decline. Kulka *et al.* (1995) and Wroblewski *et al.* (1995) did look at the winter distribution and movements of northern cod in two dimensions employing spatial methods but these analyses, using commercial fishing data, were restricted to the offshore fishing grounds (see Fig. 1). In spite of the intense research on the subject of northern cod distribution, the spatial changes and their proximal causes occurring prior to the collapse of the stock are still not clearly understood. This paper is intended to add to the knowledge of distributional changes that occurred just prior to and during the decline.

Catch rate data from fishing sets on their own, do not form an index of abundance. Rather, these point data reflect only local fish density unless the areal extent of the stock and distribution within that area remain constant over time. This is rarely the case with fish. Thus, in order to derive an index of abundance from catch rate data, a spatial component must be incorporated. That is, the point observations must be converted to a continuos surface that depicts differential density and it must encompass the extent of the stock. Spatial techniques such as potential mapping or kriging yield surface (continuos) interpretations of distribution from the point (fishing set) data and also facilitate analyses of spatial patterns and changes. Given that these techniques produce density surfaces having both an areal and a fish density component, they can also be adapted to produce indices of abundance, similar to what was done using commercial winter fishery data (Kulka *et al.* 1996).

Indices of abundance based on fishing success have been used for calibrating Sequential Population Analysis (SPA) models to project future yields and provide a basis for advice on fishery management. Incorporating such abundance indices in SPA assumes that catch rate (catch per standardised tow in the case of research vessel data) is directly proportional to fish stock abundance. To satisfy this assumption, Gulland (1955) proposed stratification of the total area of stock distribution into sub-areas within which density could be considered constant. Overall stock density is taken as the weighted mean of the sub-areas. In this way, distribution of the fish need not remain constant. Density so calculated can be taken as a measure of stock abundance, where total stock distributional area is assumed constant. However, if stock area is varied, then abundance is equal to Gulland's overall density multiplied by stock area. With this approach, changes in the spatial distribution of fish can be taken into account in deriving a stock abundance index (Kulka *et al.* 1996).

Based on Gulland's principle, a GIS (Geographical Information Systems) tool, potential mapping in SPANS (TYDAC Research Inc., Anon. 1997) is used to create density surfaces. With this technique, this paper looks at the distribution and biomass trends in northern cod in NAFO Divs. 2J, 3K and 3L (Fig.1) using fall survey data. The method of biomass estimation used here is adapted from (Kulka *et al.* 1996) who used potential mapping of commercial fisheries data to account for changes in stock distribution. This tool facilitated a spatial analysis of changes in distribution and biomass of the fish to the finest scale of the data not possible with more conventional statistical analyses. These changes were then spatially related to an environmental variable, bottom temperature and to offshore fishing pressure, both cited as causes of the decline of northern cod.

Methods

Catch, effort and bottom temperatures along with other data have routinely been collected during bottom trawl research surveys for the various areas around Newfoundland. For this study, fall research trawl set data (summer data were used in 1984 in NAFO Div. 3L) collected from 1983 to 1996 were converted to surface plots to describe the distribution of cod in NAFO Divisions 2J, 3K and 3L, to estimate abundance and to relate the distributional patterns to bottom temperature. Doubleday (1981) provides a summary of the stratified-random survey design adopted after 1970 to survey the waters of the Atlantic regions.

In 1995 there was a change of survey gear from Engels 145 to Campellan 1800 bottom trawls and over the period of study, two vessels were employed at different times for the survey. Thus, the catch rate data from each fishing set was first standardised with respect to gear and vessel as described in (Stansbury 1997, Warren 1996 and Warren *et al.* 1997). The point data consisting of standardised catch per tow and corresponding bottom temperature were then imported into SPANS using latitude and longitude at the start of the set as the geo-reference and standard catch per tow as measures of fish density. Bottom temperatures as recorded by net mounted CTD, BT or XBT included with each set observation were also included in the spatial data set.

The potential mapping procedure in SPANS, Anon. (1997) was used to convert the point data (catch rate by set) into a continuous surface depicting differential densities of fish (catch rate subareas). The method transforms points to surfaces by placing a circle around each point and averaging the values of all points that fall within the circle. The procedure is repeated for each point. The procedure effectively smoothes the data at its maximum resolution, i.e. at the spatial distance of survey fishing sets, by averaging the catch rates of all fishing sets that occurred within the chosen radius of the scanning circle. A further averaging takes place where the circles overlap and the resulting values are assigned to the underlying quadcell (a quadcell being a variable sized raster dividing the study area into a fine grid). An integration of classified quadcells forms a density surface analogous to Gulland's subareas. Refer to Anon. (1997) and Kulka (1998) for a more detailed technical description of the potential mapping method and its application to mapping and biomass analyses of marine species.

The distance between sampling points in the survey, ranging from about 20 to 70 km determined the circle radius, such that circle size was increased until there were no gaps in the resulting surface. Further increasing circle size increasingly smoothes the data to a point where a single circle encompassing all points results in a single stratum with an average catch rate (density estimate) of all points. Thus, the smallest circle that can provide complete coverage of the survey area, the better the definition of spatial variation of fish density. A series of circle sizes were tested for 1985 namely circles with 2 to 42 km. radii by 2 km intervals (refer to Kulka 1998 for details of the analysis). A scanning circle with radius 31 km was chosen as the smallest that would create a surface with minimal gaps. Because the surveyed area was very similar from year to year, the study area periphery was set by a 'cookie cut' (referred to as a basemap cut in SPANS) such that the resulting density surface was constrained on all sides by the land/water boundary, the 1000 m depth contour and the 2J and 3L NAFO Division lines. Within the bounds of NAFO Divs. 2J, 3K and 3L, this resulted in relatively constant surface size of the study averaging 354,912 km^2, varying slightly because of un-surveyed grounds close to the coast in some years. This approximates the area of the depth strata used in the random stratified design that covered 354,000 km^2.

For the purpose of biomass estimation using the SPANdex (SPANS index) method (after Kulka *et al.* 1996), the survey area thus defined was broken out into 15 equal area density strata or classes as produced from the potential mapping procedure. Each stratum covered about 6.7% or $1/15^{th}$ of the survey area across all years. Being related to a complex distribution of fish, each stratum was not necessarily contiguous and each one varied from year to year in terms of shape and location, dependant on the distribution of the fish. This approach to stratification of the survey area differs from the STRAP method in several important ways. The stratified random survey design consists of many more strata (76 in NAFO Div. 2J, 3K and 3L), those strata are fixed in space over time, are delineated primarily by bottom depth rather than fish density and each strata is contiguous. As well, for Strap, where there were no sets within particular strata, a biomass was estimated for those strata using a multiplicative model (Murphy et al. 1997). This was not necessary for the SPANdex approach.

Similar to STRAP, a mean catch rate was calculated for each stratum from the all of the points (sets) that fell within the bounds of the stratum. Each SPANdex stratum contained an average of 32 survey points (total average of 487 points per year) as compared to between 2 and 26 for the STRAP random stratified design. A midpoint value of the class boundaries was also calculated for comparison to the mean of the points within strata. The mean (and midpoint) and area of each class were used to estimate a biomass index using the formula from Kulka *et al.* (1996):

$$\mathbf{B} = {}^{n}\Sigma\ \{(\mathbf{a} \times \mathbf{c})/[(\mathbf{t} \times \mathbf{w})/\mathbf{h})]\} \qquad \text{Equation 1}$$

where **B**=biomass index
n=number of catch rate classes
a=area of catch rate class (km^2)
c=mean (or midpoint) of catch rate class (t/hr)
t=average tow length (km)
w=wingspread of net (km)
h=average number of hours per tow.

W, wingspread of net was 0.014 km for 1983 to 1994 and 0.01681 km. for 1995-96 when the gear was changed from Engel to Campelen bottom trawl gear. Engel catches were converted to Campelen equivalents. The resulting area of the survey as derived from SPANdex varied slightly from year to year due to changing distribution of survey sets. A biomass standardized to the random stratified survey area was also calculated by multiplying the ratio of the random stratified area and the SPANdex area by the SPANdex biomass.

For the fish density maps produced to depict annual distribution of cod, 15 strata were used For the maps, each stratum was set with equal area in the first survey year (1983). The strata class bounds (catch per tow legend values) were then held constant across years (a single legend for all years) so that varying amounts of each grey shade displayed depicting a density level would vary, reflecting relative changes in density. Similarly, bottom temperature maps were created using 15 strata of equal size varying from –1.6 to 3.36+ ^{0} C.

Results

Distribution

Figure 2a-d shows the annual distribution of cod during the fall (Nov.-Dec.) survey period from 1983 to 1996 in NAFO Divs. 2J, 3K and 3L. In every year up to 1990, the cod were found to be aggregated (at greater than 100 kg. per tow) at three locations on the Labrador Shelf and one on the Grand Bank as delineated by four boxes (hereafter referred to as North, Middle, South, Grand Bank) illustrated in Fig. 1, right panel. These areas, where density exceeded 100 kg. per tow contained the large majority of the biomass, at least 80% in all years. This indicates that cod even in "normal" years are highly aggregated. Density at each of these locations was not completely homogenous such that in some years, patches where density exceeded 200 kg per tow were separated by areas of slightly lower density.

These concentrations also showed some variability in extent and location from year to year but in general, the pattern was consistent up to about 1986. Note that the absence of a South concentration along the shelf edge in 1984 is likely the result of summer survey data being used that year for NAFO Division 3L when most of the South cod are likely to be closer to shore. The North (northern and western most) concentration of the three located on the Labrador Shelf covered the greatest area extending over an average of 200,000 km^2 prior to 1987. Fig. 2. and Fig. 3, North panel show that after 1986, this area of concentration declined rapidly in size until it contracted southward in 1989-91 finally encompassing only 25,000 km^2 centred southward at Lat. 53^0 in 1991 and disappearing in 1992. As well as originally being the largest concentration and extending furthest north in the earliest years of the study, this concentration was also located closest to the coast in relatively shallow water extending from Lat. 50^0 at the north coast of Newfoundland to Lat. 55^0 at the NAFO Div. 2J/2H border and shelf edge. It may be that given its proximity to the coast, this concentration may be at an earlier stage of the migration offshore. Thus, the observed variation in inter-annual distribution of this concentration may in part be due to timing of the survey (fall) with respect to degree of migration of the cod offshore. That is, the fish at the time of the survey may have been at varying stages of the migration among years.

The middle concentration, extending from about Lat. 51^0 to Lat. 53^0 (see Fig. 1, right panel for its delineation) was located closer to the shelf edge than the North concentration. However, it did extend shoreward into the Funk Island Deep toward the north-east coast of Newfoundland in some years (Fig. 2). The North and Middle concentrations were nearly joined to the south in 1986 and 1989 perhaps reflecting an earlier stage of the migration from the inshore than in the other years. This Middle concentration, smaller than the North concentration in the earlier years, generally increased in size from about 50,000 km^2 in 1983-85 to about 150,000 km^2 in 1989 then declined rapidly until its disappearance in 1991 (Fig. 3). Its area was (perhaps) anomalously large in 1986 (as was observed to a lesser extent in the North and South concentrations), the year of the high biomass estimate driven by a very large catch for one of the sets.

The size of the South concentration remained relatively stable in size at around 50,000 km^2 where density exceeded 100 kg. per tow until 1991 (except the 1986 peak) then declined and disappeared. It was the last of the original four concentrations that were gone by 1994 (Fig. 2 and 3). It was the least variable of the concentrations in terms of location, showing its greatest divergence from its "normal" shelf edge distribution straddling the NAFO Div. 3K/3L border in 1984 when the summer survey data were used. In that year, it was located farther west into the Funk Island Deep perhaps as a result of being at an earlier stage of migration offshore. In all years up to 1993, there were some areas of moderate density extending directly shoreward to the northeast coast from the main body of fish located on the shelf edge. All three concentrations on the edge of the Labrador Shelf, North, Middle and South extended toward the coast to varying degrees by year. This suggests that the different concentrations may have been at different stages in their offshore migration among years.

The Grand Bank concentration on the other hand, exhibited no such association to the land except perhaps in 1985 and 1995 when there was a small but separate concentration of fish located at the mouth of St. Mary's Bay just north of Green Bank. It should be noted that only one or two sets defined these mini-concentrations observed in 1985 and 1995. Otherwise, the Grand Bank concentration consisted of one or two high (> 100 kg. per tow) density concentrations straddling the NAFO Div. 3L/3N/3O border, separate from the three concentrations to the north. The extent of this concentration peaked at 145,00 km^2 in 1984, declining to 22,000 km^2 in 1988, expanding again in 1990 for one year at 85,000 km^2 then disappearing the next year (Fig. 3). In the final three years, 1994 to 1996, the entire study area consisted of very low densities of cod generally less than 5 kg per tow.

Biomass

Biomass calculated by the SPANdex (SPANS index) method for the entire stock area in three ways (Table 1). The first method uses midpoint of the density classes. The second uses mean kg. per tow of the sets that fell within each stratum boundary. The third uses total area from the random stratified design to standardize area among years (SPANdex biomass multiplied by ratio of total survey STRAP area and SPANdex area). The three yielded a nearly identical trend over years (Fig. 4a and Table 1). The mean estimates were consistently lower by about 7-10% than the midpoint estimate. This is because the catch rate data are strongly skewed to the right leading to a consistently different mean and mode within strata. The estimate chosen was the mean adjusted to STRAP survey area because it uses the same method as STRAP in assigning an average density value to each stratum.

Biomass of the total stock area as calculated using the SPANdex (mean) method was very similar to that calculated by STRAP except in 1983 and 1984 when the SPANdex estimates were 20 and 30 % higher respectively (Fig. 4). Both methods used the same point data and areal expansion to calculate biomass within each stratum. The difference biomass estimates between the two methods lies in the way that the survey area is stratified. There were large percent differences observed in 1992 and 1996. However, at this time, biomass was low. In absolute terms, the difference between the two estimates was small. Some of the differences may also be due to the estimation of biomass using a multiplicative model for unsampled strata in STRAP.

The cod in all years were aggregated such that on average, about 77% of the biomass was concentrated into 20% of the survey area although some cod were found over most of the area. This level of concentration varied considerably among years. Figure 5a shows that up to 1988, the value fluctuated around 71% but rose rapidly in 1898-1991 to an average 89% when the concentrations of cod hyper-aggregated. The values then returned to 76% after 1991 although in those latter years, the density generally did not exceed 10 fish per tow except over a very small area in 1991. Figure 5b shows the relationship between biomass and area during 1983 when the biomass was less aggregated (and larger) and in 1990 when hyper-aggregation had peaked. In 1990, the curvilinear relationship is much steeper (longer tail to the left), confirming that the biomass was concentrated over a smaller area than in others years. The straight line shows the relationship where the cod would be evenly distributed.

Biomass trends within each of the four boxes, North, Middle, South and Grand Bank depicted on Fig. 1, right panel are shown in Fig. 6a (biomass) and b (percent of total biomass). It shows that similar to the extent of dense (>100 kg. per tow) concentrations of cod, the biomass in the North box was initially highest of all areas at about 50% (60% of North, Middle, South areas) of the biomass from 1983 to 1985. It then declined gradually to 10% in 1992. The Middle box contained a smaller proportion of the overall biomass except in 1987. Between 1983 and 1985, it accounted for an average of only 5%, increasing to about 31% between 1987 and 1991 then declining to previous levels.

Figure 6c depicting the proportion of cod among the Labrador Shelf concentrations, North, Middle and South, shows that the North area contained most of the biomass up to 1986. There was a proportionate increase in the biomass in the Middle area during 1986 to 1991 from about 10% to 30% then a subsequent drop. The South area increased over time from about 20% (1983 to 1987) to a peak of 80% in 1992-93. After 1992, following the decline of the stock, the three areas shared a more similar proportion of the remaining biomass, the South area with more of the biomass. As noted above, the fish at the time of the survey may had been at varying stages of the migration among years, confounding the observed changes across years. Thus, in terms of relative biomass, the North area was at its greatest extent between 1983 and 1985, the Middle area in 1986-1990 and the South area in 1991-93.

Bottom Temperature

Fall bottoms temperatures depicted in annual gray shade surfaces for 1983 to 1996 varied considerably over the extent of the study area from year to year (Fig. 7a-d). There were three distinct areas noted in all years; a cold area adjacent to the coast of Labrador from Lat 50^0 to Lat.

55^0 in waters where the depth was generally less than 250 m. (see Fig. 9a), another cold area on the Grand Bank where depth was less than 200 m and a warm area along the Labrador Shelf edge including the adjacent (shoreward) deep channels.

In most years, only the deep channels between the banks, namely Cartwright and Hawke Channels and Funk Island Deep contained bottom water greater than 2^0 C. In warm years i.e. 1983, 1986 and 1988 warm water greater than 2^0 C covered the bottom over a much greater part of the Belle island Bank. Hamilton and Funk Island Bank bottom water generally remained in the 0.1-1.5^0 C range.

The extent of the CIL (cold intermediate layer) influenced the shallow Grand Bank and inner Labrador Shelf areas and the degree of the warm slope water incursion onto the shelf affected the extent of warm shelf edge waters. Only in 1984, the coldest year did sub-zero temperatures reach the shelf edge to the north. The cold Grand Bank water mass showed the least variation from year to year generally remaining below about -0.6^0 C except onto the shallowest part of the bank to the southeast where it was slightly warmer (average 0 to 1.0^0 C) in some years.

Figure 8 shows the relationship between bottom temperature and fish density averaged over the entire area. This relationship, grouped into three time periods, pre-collapse (1983-86), collapse (1987-91) and post-collapse (1992-96) in Figure 8a shows three different patterns although in most years the areas of higher cod density were generally associated with higher temperatures. For 1983-86, the figure suggests no relationship between density of the fish and bottom temperature. The entire range of densities were consistently found in an average bottom temperature of about 1.0^0 C. However, the annual plots of this relationship illustrated in Fig. 8b shows a great deal of variation among years within this time period. The most dramatically different year was 1984. The areas of highest density (and most of the cod) were found where bottom temperature averaged less than 0^0 C, between 1 and 3^0 C lower than any other year (1984 was the coldest year in the series). The warmest year, 1986, showed the highest average temperature where cod were most dense. On the other hand, the pattern amongst years within the latter two year groups was consistent. In 1987-91, the fish tended to be more aggregated in warmer temperatures mainly where bottom waters averaged between 1.5 and 2.4^0 C. In 1992-96, the difference between low density and high density areas was less dramatic although denser concentrations were found in warmer areas. The variable annual patterns in bottom temperatures, the fairly stable distributions of cod during the earlier years (pre-collapse) and the fluctuating temperature/density relationships indicate little relationship between bottom temperature and density. The cod tended to be found in warm water in warm years and cold water in cold years. Thus, the cod were found to have retained their distributional patterns among years in spite of substantial inter-annual variations in bottom temperature in the area.

The Grand Bank area in terms of extent of the area occupied by cold/warm bottom water tended to vary independently from the Labrador Shelf/slope areas among years. However, the extent of the warmer slope water tended to be greater in years when the extent of the cold Labrador coastal waters was at its smallest. This relationship did vary in certain years. For example, in 1983 and perhaps 1994, the cold Labrador coastal waters and the warm slope waters were both fairly extensive. Thus, the extent of the two water masses were not completely inversely related.

The area of greatest inter-annual variation was that of the cold coastal Labrador water. Figure 9a shows a "cold box" encompassing 90,777 km^2 (about 25% of the total survey area) delineating this cold area much of the North concentration. The coldest year in the "cold box" (and also over the entire study area) was 1984. Bottom waters less than 0.77^0 C and less than 0.1^0 C, extended over 83,827 and 72,714 km^2 respectively in that year. Compare this to the warmest year, 1986 where there was no area with less than 0.1^0 C and only 13,077 km^2 was overlaid by water less than 0.77^0 C.

Figure 9b, based on a spatial analysis within that "cold box" compares extent of the coldest waters with the extent of dense cod concentrations. This area where cold CIL water reaches the bottom to a varying extent among years is associated with the North concentration of cod although these cod also extended to the north into the warm slope water at the border of NAFO Div. 2H and 2J. The average bottom temperature within the "cold box" varied considerably from 1.6^0 C in 1986 to –0.7^0 C in 1984 (Fig. 9c) fluctuating with no apparent trend from year to year. The years 1983 to 1985 were cold, 1986 was the warmest year, 1987 was again cold, 1988 to 1992 relatively warm, 1993 cold and 1994 to 1996 warming. The extent of the coldest water, less than –0.1^0 C, fluctuated correspondingly, areal extent being greatest in years where average temperature was coldest. Percent of area occupied by cold (–0.1^0 C) water varied from 0% in 1984 to 69% in 1986. Except in a couple of years, greater than 85% of the total box area was occupied by bottom water less than 1.89^0 C and all of this area was constrained to the northeast corner approaching the shelf edge.

Before 1989, there was some indication that cod density in the "cold box" may bear a limited relationship with bottom temperature. For example, in 1986 and 1988, two years when the extent of cold water was lowest, cod density was higher with respect to adjacent colder years. However, cod density was very similar between the cold years, 1983, 1984, 1985 and 1987 of the pre-decline period and the warm year, 1988. How much these patterns are confounded by the timing of the migration is unclear. For example, if the survey period occurred later in the migration, then average density in this area would be expected to be lower as the fish concentrate in a smaller area to the north, more typical of the winter distribution. In 1989 and thereafter, the cod density in the box declined and stabilized at very low levels. This occurred regardless of the extent of the cold bottom water in the box. There was no increase in cod density during the recent warmer years, 1995 and 1996. Even moderate densities (between 10 and 100 kg. per tow) were not recorded in the "cold box" after 1992.

Figure 9d relates extent of the high density cod concentrations (> 100 kg. per tow) in the "cold box" to extent of the coldest water (< -0.1^0 C). Density remained low or zero after 1991 after the decline. Before then, with the exception of 1986, higher area of cold water tended to correspond to a greater areal extent of high-density cod. In 1986, extent of high cod density in this warmest year (no area where bottom temperature was < -0.1^0 C) was at its highest.

Discussion

Biomass Estimation – SPANdex vs. STRAP

The extent to which spatial distribution can be incorporated in analysis of catch rate data depends on the geographical scale in the data. Paloheimo and Dickie (1964) proposed that the relationship between catch rate and stock abundance is a function of the number, size and density of fish schools. Thus, a spatial scale of sampling at the level of fish schools would be required to take full account of distributional changes in catch rate analysis. Rose (1993) found that schools of cod off eastern Newfoundland extended over about 2.5 km to 20 km, a finer scale than is available with the current research sampling intensity. Thus, survey sampling intensity would have to be increased such that the sets are less than 20 km apart to capture the spatial variation at the level of fish schools. Current sampling distances for the fall survey average about 40-45 (range of about 20-70) km. Thus, regardless of how the data are analysed, survey sets would have to be denser than at present to assure a full accounting the distribution. However, there remains other factors such as movement of the schools, fish above the gear, gear behaviour etc. that affect catchability. In contrast, data from the winter commercial fishery (Kulka *et al.* 1996) benefited from a much tighter set spacing, about 2.5 km, less where there were significant amounts of fish. However, these commercial data had another source of variability introduced by the use of many sampling platforms.

A method referred to as STRAP (Stratified Analysis Programs, Smith and Somerton 1981) is commonly used to estimate cod and other fish biomass indices from research vessel surveys. Its sampling design is based on Gulland's (1955) principle of stratifying the surveyed area into sections, each with homogeneous fish density. The sampling scheme that is used to obtain the data for STRAP is a random stratified survey design with depth as the primary stratifying variable. That is, the survey area is divided into strata whose borders largely follow contours of depth This (or any other approach) to surveying assumes that density of the fish is constant within strata. In this case, the assumption is that cod density is related to depth. However, this may not necessarily be the case since fish concentrations are often found to be discontinuous along lines of depth. It is clear from this analysis that depth may not relate closely to fish density.

The SPANdex technique used in this study is adapted from Kulka *et al.* (1996) who applied it to commercial catch rate data. It is also well suited for spatially analysing research survey data because it converts point estimates, in this case individual set catch rates, into continuous surfaces (density subareas) that perform as survey strata. Observed fish density is used as the stratifying variable thus potentially reducing within strata variability of density. The larger, more constant number of sets per strata (32) versus 2-26 for STRAP also likely further reduces the estimate of variation. An added advantage is that extent and location of density constant subareas is allowed to vary according to distributional changes of the fish. That is, the technique makes use of the geo-referenced catch rate data to define location and extent of the density strata. The strata vary over time taking into account stock distributional shifts with a resulting lower within strata variability.

<u>Distributional shifts</u>

This approach taken with this analysis of the research survey data also provides the flexibility to examine distributional and associated biomass changes in any user-defined subarea within of the extent of the stock based on observed distributional patterns. Smith and Somerton (1981) indicated that their STRAP system was designed for ease of analysis of the database. However, it does not provide for examination or analysis of the fish distributions nor does it allow for a breakdown of stock areas except by NAFO Divisions. This and other analyses show that the standard 2J, 3K and 3L Divisional boundaries do not always conform to stock or related bio-physical sub-boundaries. The distributions are often dynamic and extend differentially among years across standard boundaries such as NAFO Divisions. This can confound the results of analyses that adhere to those boundaries.

Lilly (1994) based on 1980-88 averaged data reported the presence of four areas of concentration of the cod in the fall. He also noted that with some variations the pattern of concentration was similar among years. These areas corresponded closely with the North, Middle, South and Grand Bank concentrations reported in this paper However, there was a substantial difference in the distribution of cod observed during the winter months as reported by Kulka *et al.* (1995), Kulka *et al.* (1996) and Wroblewski *et al.* (1995). Between the Nov.-Dec. survey period and the Jan.-Apr. fishery offshore, the cod concentrated further offshore to deeper, warmer waters. There, the fish formed much smaller and more dense concentrations, particularly with respect to the North concentration that was much more extensive and coastward in the fall (refer to a description of the fall migration in Lear and Greene (1984) and Rose (1993)). Regardless of time of year, winter (Kulka *et al.* 1995) after the completion of the migration or fall (this study) during the migration, the proportion of biomass on the Labrador Shelf changed among the three areas over the years. While the North declined starting in 1985, the Middle area increased between 1985 and 1987 then declined rapidly in 1992. The South increased starting in 1987 up to the collapse in 1992-93. Given that there was movement of fish along the shelf edge among the three areas (Kulka *et al.* 1995 and Wroblewski *et al.* 1995), the progressive southward change in proportion of biomass from North to South on the Labrador shelf suggests a southward shift of the biomass during the time prior to the decline starting in 1985. There was also evidence of yet another more northerly concentration of fish in earlier years. Countries other than Canada fished a dense concentration of fish straddling the NAFO DIV. 2H/J border in the 1970's. This concentration disappeared in the early 1980's. This may have been an earlier stage in the progressive southward shift and disappearance the cod.

Various authors i.e. Atkinson *et al.* 1997, deYoung and Rose (1993), Kulka *et al.* (1995), Rose *et al.* (1994), Warren (1997) also reported a shift in the distribution of northern cod leading up to the collapse of the stock. Hutchings (1996) on the other hand, based on an examination of high density survey point plots suggested that the southerly shift (involving an active movement of fish) did not occur. Based on these findings, he suggested a re-examination of changes in cod distributions prior to and during the decline. The current spatial analysis of fall survey data representing such a re-examination, shows that the cod biomass shifted over time, in terms of proportion of the biomass, extent and spatial variation of area occupied by dense concentrations of cod. The relative biomass of fish in those areas, North to South, was similar to what was observed in the winter months (Kulka *et al.* 1995) when the main body of fish, concentrated eastward along the shelf edge also showed the southward shift.

Atkinson *et al.* (1997) in an examination of size of area containing 90% of the biomass of northern cod noted a decline in the area of distribution starting in 1989, 2 years prior to the start of the decline in biomass. This pattern is comparable to the results of the current study that showed a sharp increase in proportion of cod in 20% of the stock area in 1989, indicating the commencement of hyper-aggregation. However, this study indicates even earlier distributional changes. Atkinson *et al.* (1997) also noted a dramatic increase in the area containing 90% of the biomass in 1993. The current study indicated this hypo-aggregation (a reduction in biomass per area proportions) occurred in 1992 when the percentage returned to levels just slightly higher than those observed before 1989. Hilborn and Walters (1992) referred to the behaviour of stocks where local densities remained constant over a range of abundance as hyper-stability. In this case, the cod went beyond hyper-stability by increasing their local density rather than remaining stable while extent of the high density areas decreased, just as the decline in biomass commenced. It is clear that when interpreting catch rates as an index of abundance, this type of behaviour that can take place while a population changes can lead to erroneous conclusions regarding stock size. The interpretation of catch rate data without a spatial component under any circumstance can be misleading.

The Grand Bank concentration declined as well during the 1980's and early 1990's as did the contiguous body of fish in NAFO Divs. 3Nand 3O but there was no evidence of a shift of biomass from the Labrador Shelf to the north into this area. Although this Grand Bank concentration falls within the southern portion of NAFO Div. 3L, it is a continuum of the concentration of fish in NAFO Divs. 3N and 3O. Templeman (1962), Lear (1984) and Taggart *et al.* (1995) suggested that this group overlapping the NAFO Div. 3L border represents a sub-stock restricted to the Grand Bank. Kulka et al. (1995) and Wroblewski et al. (1995) support this view. In their analysis of movement cod during the winter saw no evidence of movement between the Grand Bank and the Labrador Shelf concentrations while showing movements of the fish schools along the edge of the Labrador Shelf between the North, Middle and South areas. Fall survey and winter fishery data consistently showed very low density or zero sets between the concentrations on the shelf edge and Labrador Shelf to the east and north, and the concentration on the top of the Grand Bank.

Anderson (1993) showed that younger cod distribute differently than the adults, that the juvenile cod, age 1 to 4 tended to aggregate in two areas one on the Grand Bank and one along the coast of Labrador. This Labrador distribution, particularly for the youngest years corresponded with the North concentration described in this paper. This concentration started to decline earliest suggesting that juvenile fish may have disappeared first. This contradicts the view that adults were most affected by the decline. An age dis-aggregated biomass analysis is required to examine this problem.

Cause(s) of the decline

Many authors have examined a variety of factors that may have affected the abundance of northern cod. For example, Helbig *et al.* (1992) and Hutchings *et al.* (1993) looked at the potential effect of currents, Lilly (1994) looked at temperature and capelin as a food source and Hammill and Stenson (1997) looked at seals as a predator. Perhaps the two most quoted factors in the decline are overfishing and the environment. Hutchings (1996) and Hutchings and Myers (1995) stated that there is considerable evidence to support the hypothesis that overfishing was the primary, if not sole cause of the collapse. On the other hand, the decline of the northern cod stock has been attributed to environmental causes such as temperature changes i.e. Atkinson and Bennett (1994) and Rose *et al.* (1994). The current analysis tends not support either temperature as a proximal cause affecting juvenile or adult behaviour, or overfishing offshore as leading causes of the decline.

If fishing by a cropping down affect due to offshore effort caused the decline then it would be expected that fishing pressure both in timing and intensity would correspond to the spatial decline of the cod as described here and in Kulka *et al.* (1995). This was not the case. The cod in the northern most part of the stock area declined then disappeared first. The northern area occupied by high-density concentrations (> 100 kg per tow) was the most extensive of three areas of concentration on the Labrador Shelf in the early 1980's. It then underwent a steady reduction in extent starting in 1986. The middle concentration increased in size such that it was about three times greater in size in 1989 than in the early 1980's. A similar increasing pattern during the 1980's was not observed for the southern concentration. However, the fish became increasingly more concentrated in the southern area in spite of a steady if not increasing fishing pressure in that area.

Kulka *et al.* (1995) and Wroblewski *et al.* (1995) showed that the offshore fishing was in fact limited in the most northerly part of the stock area. The area north-west of Lat. 54^0 20' was not fished at all in the 1980's and 1990's although the North concentration of cod consistently extended into this area until its disappearance. This North concentration, increasingly less fished after 1982, was the first to decline and disappear. It first underwent spatial changes during 1985-88, diminishing greatly in size in 1989-91 then disappearing in 1992.

Fishing in NAFO Div. 2J did not increase with time. Rather, effort in 2J was very low in 1984, 1985 and 1986. Most of the fishing that occurred in 2J after 1984 occurred in the southern part of the area on the Middle concentration that straddled the 2J/3K border as shown in this study and others (i.e. Lilly 1994, Shelton *et al.* 1996). Therefore, in the offshore, particularly on North concentration, there was a decrease, not an increase in fishing effort prior to the decline of the cod as is reported by Hutchings and Myers (1994).

As well, the most intensely and consistently fished concentration during all of the 1980's and 1990's, that off Tobins Point (centred at Lat. 49^0 Long. 50^0), persisted the longest, right up to the end of the fishery. If fishing pressure was the primary cause of the decline then it would seem likely that this South concentration would have declined first, not last. As well, once the offshore fishery was closed in Feb. 1992, the Tobins Point concentration continued to decline rapidly in the absence of fishing pressure. Thus a spatial analysis of the stock in relation to fishing effort distribution argues against the theory put forth by Hutchings (1996) that fishing pressure was the primary if not only cause of the decline. Offshore fishing obviously contributed significantly affecting the rate of the decline given the magnitude of the annual removals but it appears that offshore effort did not drive the decline.

Also, in order for the cod to be cropped out of a particular area they would have to stay in that area and not mix with cod in others locations. Kulka *et al.* (1995) and Wroblewski *et al.* (1995) found that the cod in fact moved along the shelf edge during the winter fishery.

The current study in conjunction with the offshore fishing effort patterns described by Kulka *et al.* (1995) and Wroblewski *et al.* (1995) suggests that neither is offshore fishing the primary cause of the decline. As noted above, Kulka *et al.* 1995 demonstrated that while the cod were concentrated along the shelf edge in the winter, there was a shift of biomass between three boxes overlaying the areas where cod tended to aggregate. They showed that during 1980 to 1991, as the biomass in the northern area declined, the biomass in the middle area increased. The southern area, lowest in 1980 steadily increased over time until it was the highest of the three areas in 1991. If neither temperature nor overfishing offshore is the leading cause of the decline, it is quite possible that the cause(s) of the decline have not been measured (detected).

Colbourne *et al.* (1997) reported that bottom temperature over much of the continental shelf off Newfoundland and Labrador was 0.5^0 to 1.0^0C below normal since 1986, during the period of pre-decline and decline of the cod. However, Hutchings (1996) concluded that the effect of environment including water temperature was small relative to the influence of fishing because of the inability of various researchers to detect an environmental influence. The comparison in the current study of bottom temperature patterns in relation to the fall adult and juvenile cod distributions do not support the hypothesis that temperature was a proximal cause of the decline in terms of affecting their fall or winter behaviour. It shows that although the North concentration was the first to disappear, large annual fluctuations in bottom temperature in the area occupied by the North concentration prior to the decline did not seem to influence (positively or negatively) density and biomass of the cod in that area. Lilly (1994) noted that the cod in NAFO Div. 2J were capable of inhabiting very cold water. The current study confirms this showing that during the 1980's, the fish did not change their migration behaviour. They continued along the same migratory routes (coined migration highway by Rose, 1993) each year toward their shelf edge wintering ground (described by Kulka *et al.* 1996) through areas where bottom temperatures underwent substantial inter-annual fluctuations. Density and biomass in the North area (the northern most migratory route) remained consistently high until 1988 in spite of the substantial bottom temperature fluctuations (1983-5, very cold, 1986 very warm, 1987 cold and 1988 warm again. The rapid decline of the cod in this area in 1989-92 then occurred in relatively warm years. These results

The winter destination of the cod along the shelf edge, although variable in terms of extent of warm water was always substantially warmer than areas shoreward where cod were scarce. As well, Kulka *et al.* (1995) noted a shift in the winter cod concentrations to deeper waters in the late 1980's that did not seem to correspond with any systematic changes in the bottom temperatures along the shelf edge during the same period.

Cadigan and Shelton (1997) in their analysis of the association between bottom temperature and 2J3KL fall cod survey catches noted that the cod tended to be found in warmer waters in warmer years, colder water in colder years and indicated that this did not make intuitive sense. The spatial comparisons in the current study help to explain why this occurred. While temperature fluctuated considerably in the 1980's prior to the decline, the cod on the Labrador Shelf did not alter their migration route to the shelf edge to avoid cold areas in the cold years. That is, it appears that the cod were not seeking or being influenced by temperature found along their migration route Their fall distribution remained similar among the (pre-decline) years regardless of bottom temperature. However, the winter (post-migratory) distribution described by Kulka *et al.* 1996 is clearly associated with the warm slope waters. Cod in other areas have also been found to have a temperature association at certain times. For example, Swain and Framer (1995) found that cod in the Gulf of St. Lawrence will select relatively cold temperatures at high levels of abundance. In any of these studies, whether temperature was an influencing factor or just concurrent with other influencing variables in these associations is unclear.

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Table 1 - Estimates of biomass using SPANdex and STRAP for 2J3KL cod, 1983-1996

	SPANdex			STRAP			
Year	Midpoint	Mean	Adjusted Mean	Strat2J	Strat3K	Strat3L	Strap
1983	1,231,545	1,133,119	1,306,022	772,492	384,498	495,838	1,652,828
1984	1,399,519	1,328,620	1,369,187	557,220	381,311	993,963	1,932,494
1985	1,123,303	1,072,478	1,058,313	472,147	209,685	464,125	1,145,957
1986	2,411,506	2,297,878	2,420,104	1,285,763	964,857	362,233	2,612,853
1987	1,281,297	1,222,158	1,253,037	491,599	303,036	325,352	1,119,987
1988	1,040,113	949,469	961,267	600,352	216,736	256,383	1,073,471
1989	1,338,981	1,265,063	1,274,692	425,387	830,045	172,300	1,427,732
1990	1,166,320	1,140,877	1,143,019	128,352	624,993	395,567	1,148,912
1991	835,207	759,275	818,653	150,136	467,502	144,684	762,322
1992	265,126	250,353	265,006	12,795	35,344	147,158	195,297
1993	82,341	65,868	72,841	5,129	14,226	36,813	56,168
1994	10,171	9,309	9,757	2,694	4,241	4,291	11,226
1995	14,948	13,766	14,313	2,314	4,598	7,735	14,647
1996	24,453	23,483	21,909	4,263	5,457	7,067	16,787
Average	**873,202**	**823,694**	**856,294**	**350,760**	**317,609**	**272,394**	**940,763**

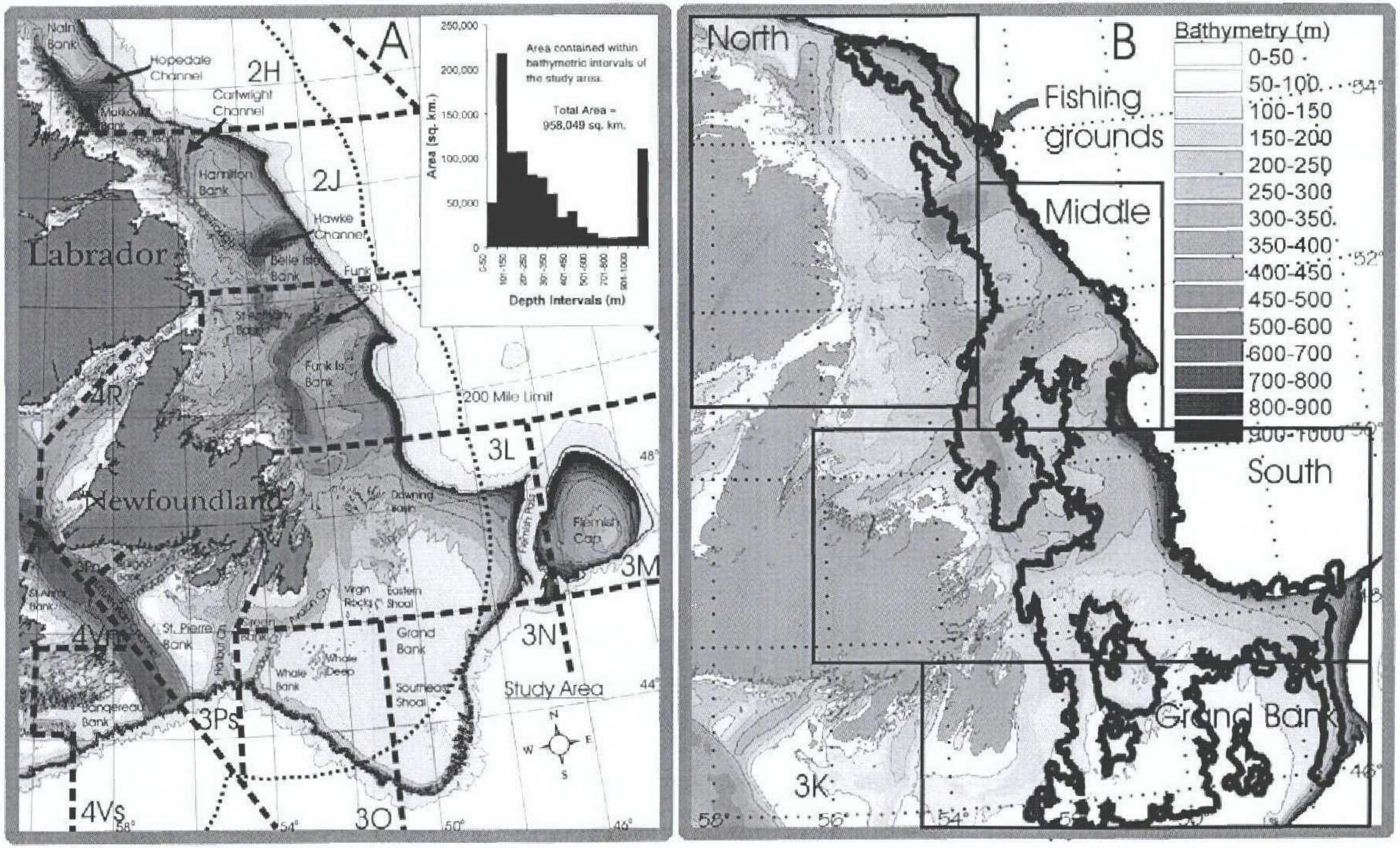

Figure 1 - A, left panel shows geographic features and NAFO Divisions of the area occupied by northern (2J3KL) cod and surrounding areas. B, the right panel shows the north middle, south and Grand Bank boxes corresponding to the high density concentrations. It also shows the extent of the commercial fishing grounds (1980-92, after Kulka et al 1996).

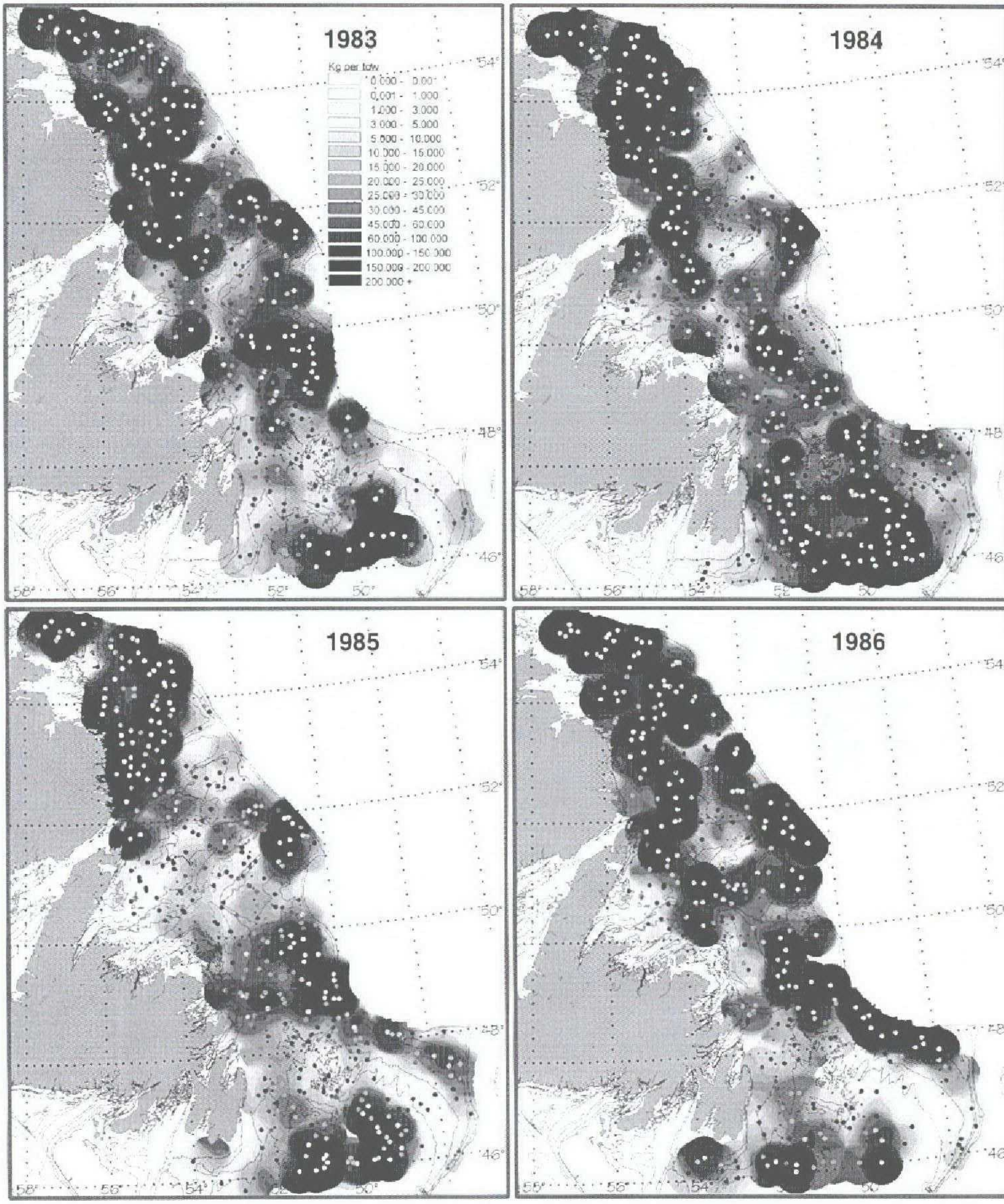

Figure 2a - Changes in the distribution of cod based on fall research surveys, 1983 to 1986. Grey shades represent levels of density (kg. Per tow) as specified in the legend.

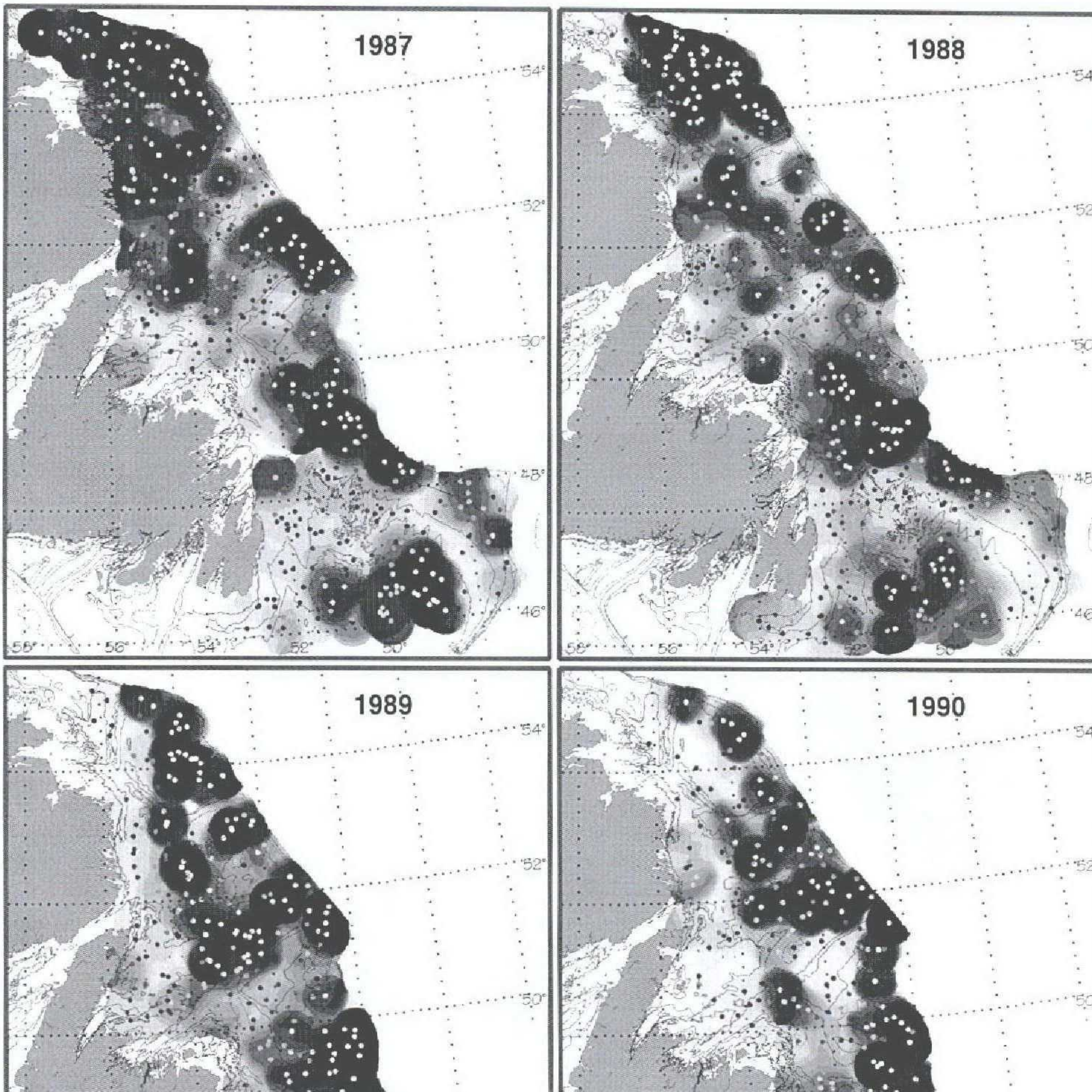

Figure 2b - Changes in the distribution of cod based on fall research surveys, 1983 to 1986. Grey shades represent levels of density (kg. per tow) as specified in the legend.

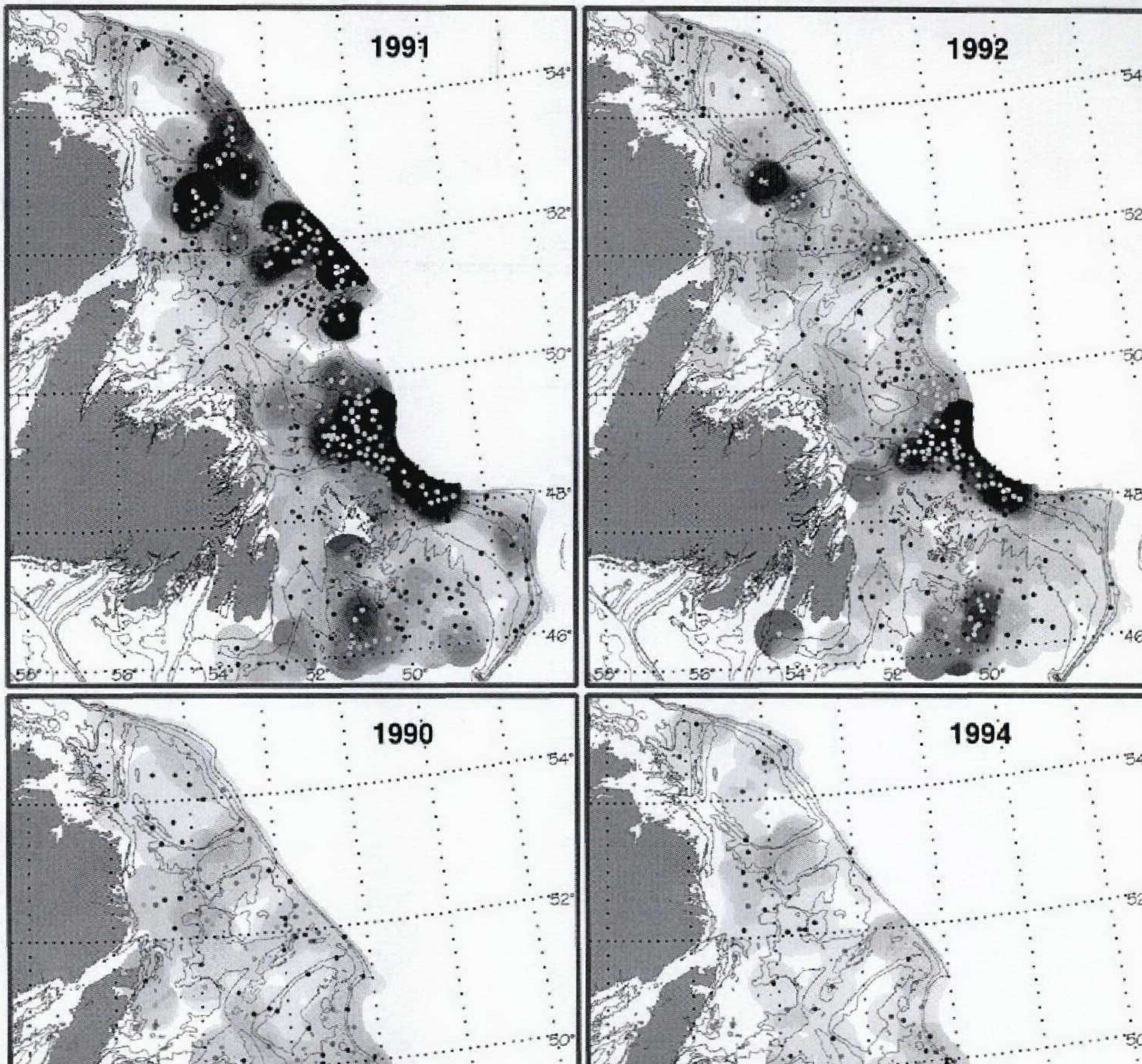

Figure 2c - Changes in the distribution of cod based on fall research surveys, 1991 to 1994. Grey shades represent levels of density (kg. per tow) as specified in the legend.

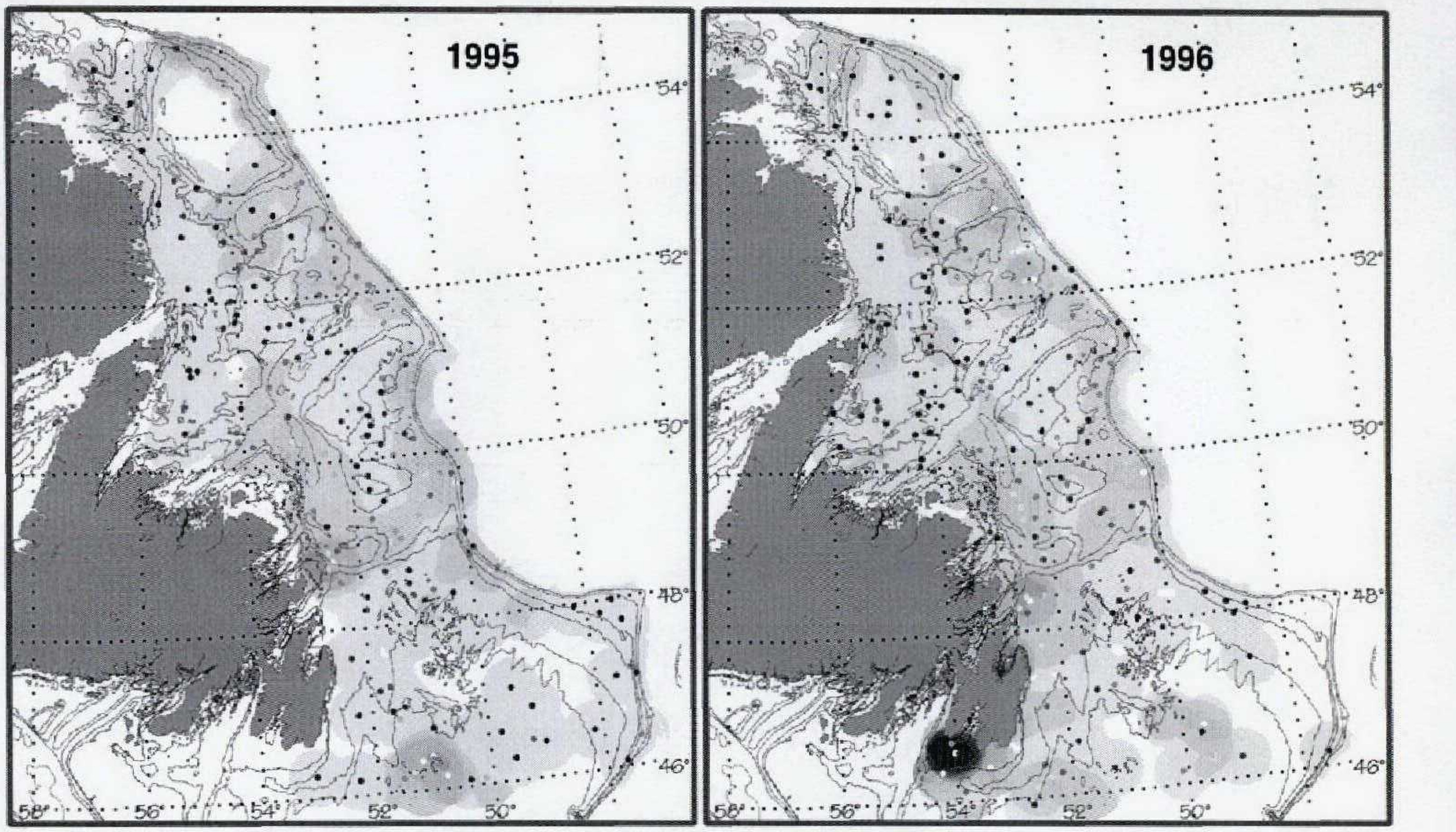

Figure 2d - Changes in the distribution of cod based on fall research surveys, 1995- 1996. Grey shades represent levels of density (kg. per tow) as specified in the legend.

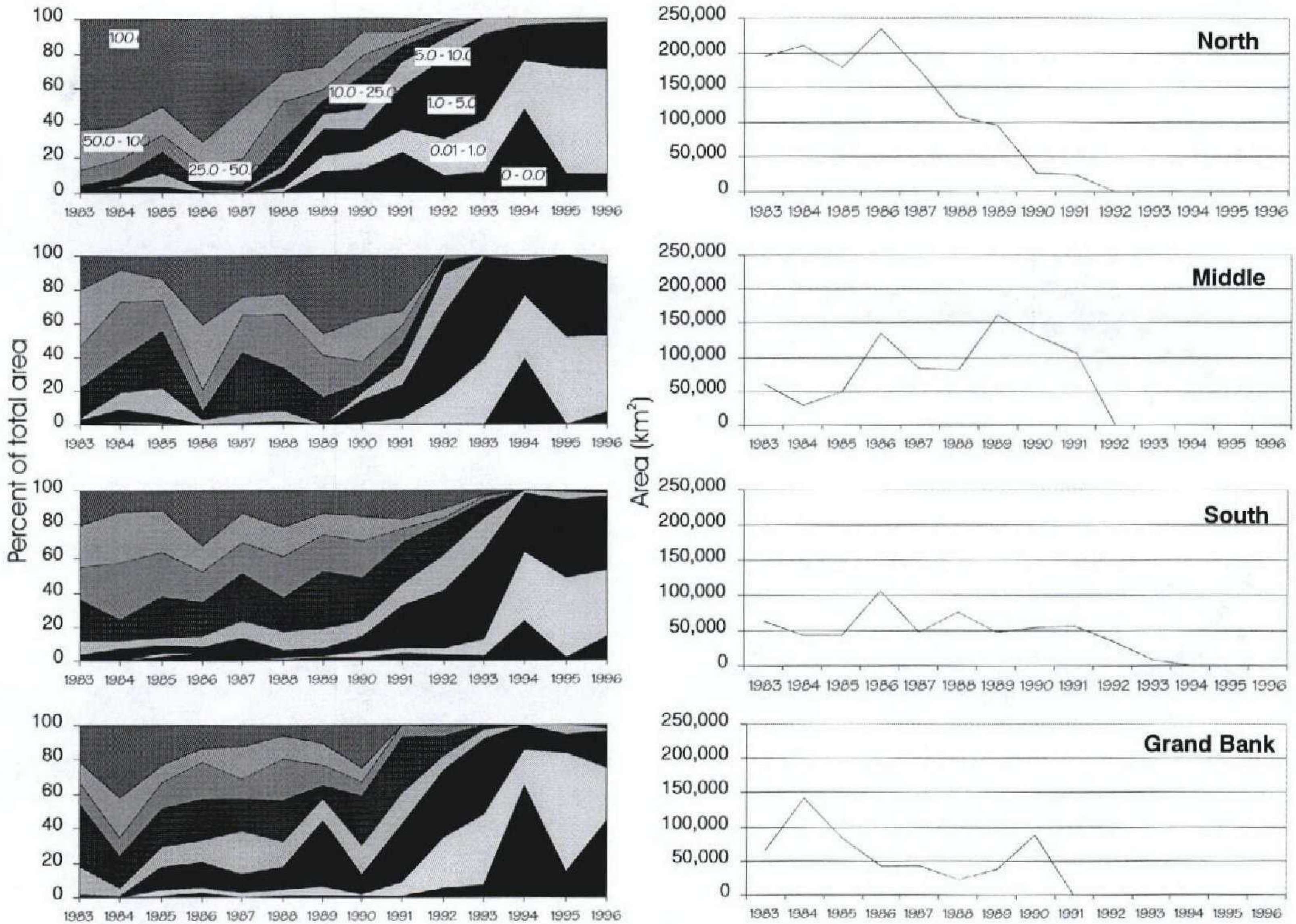

Figure 3- Changes in extent of density categories. From top to bottom, the areas are north, middle and south as delineated by the boxed areas shown in Figure 1b. The left column shows percent of the total area in each box by density class. Density classes are specified in the upper left panel. The right column shows, for each box, the changes in areal extent in km² of the highest density class, where kg per tow exceeded 100.

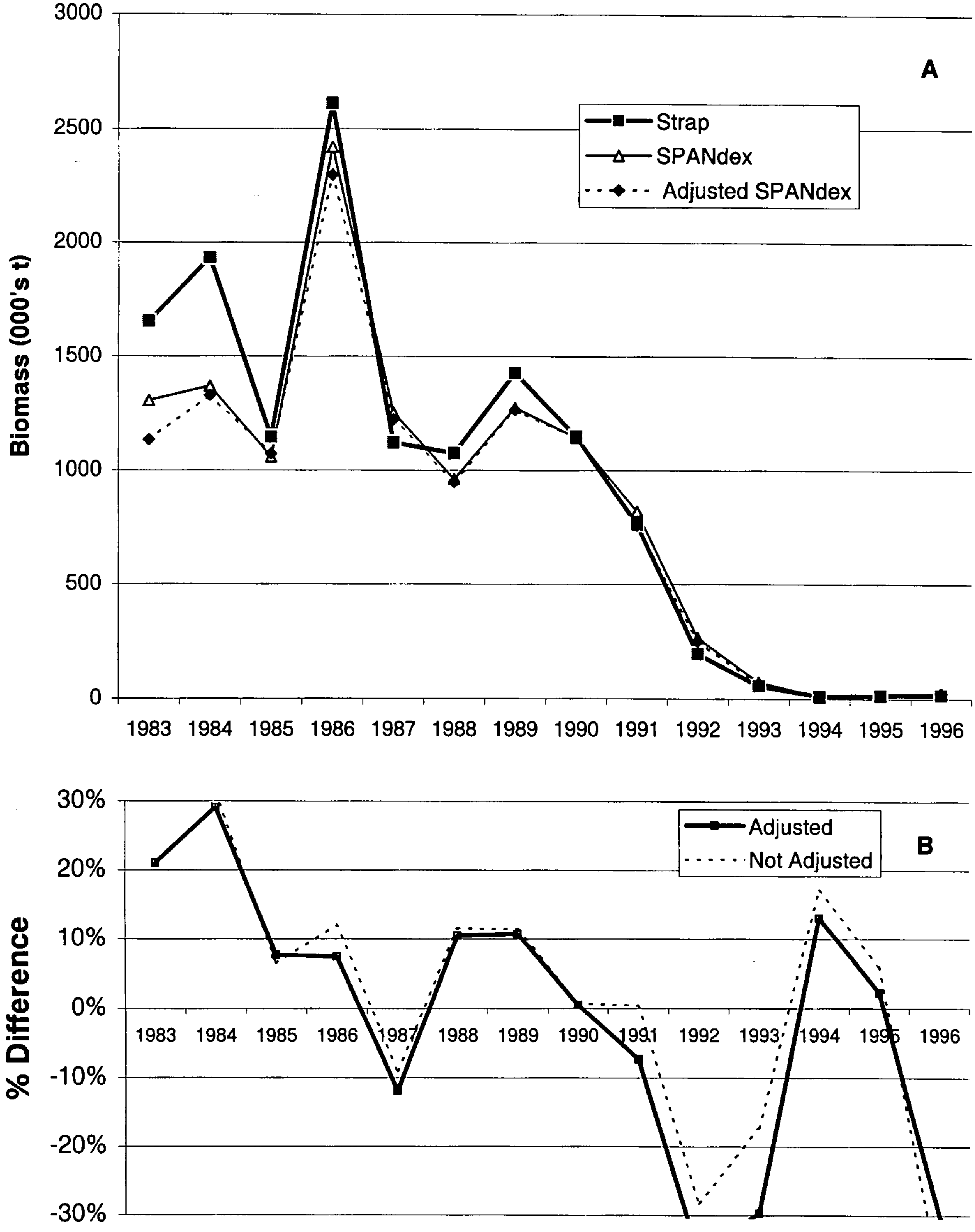

Figure 4 - A. Comparison of SPANdex and STRAP generated biomass indices for 2J3KL cod fall survey data. The adjusted SPANdex is adjusted to a constant area of 540,000 km2.
B. Difference between the two indices relative to SPANdex (adjusted).

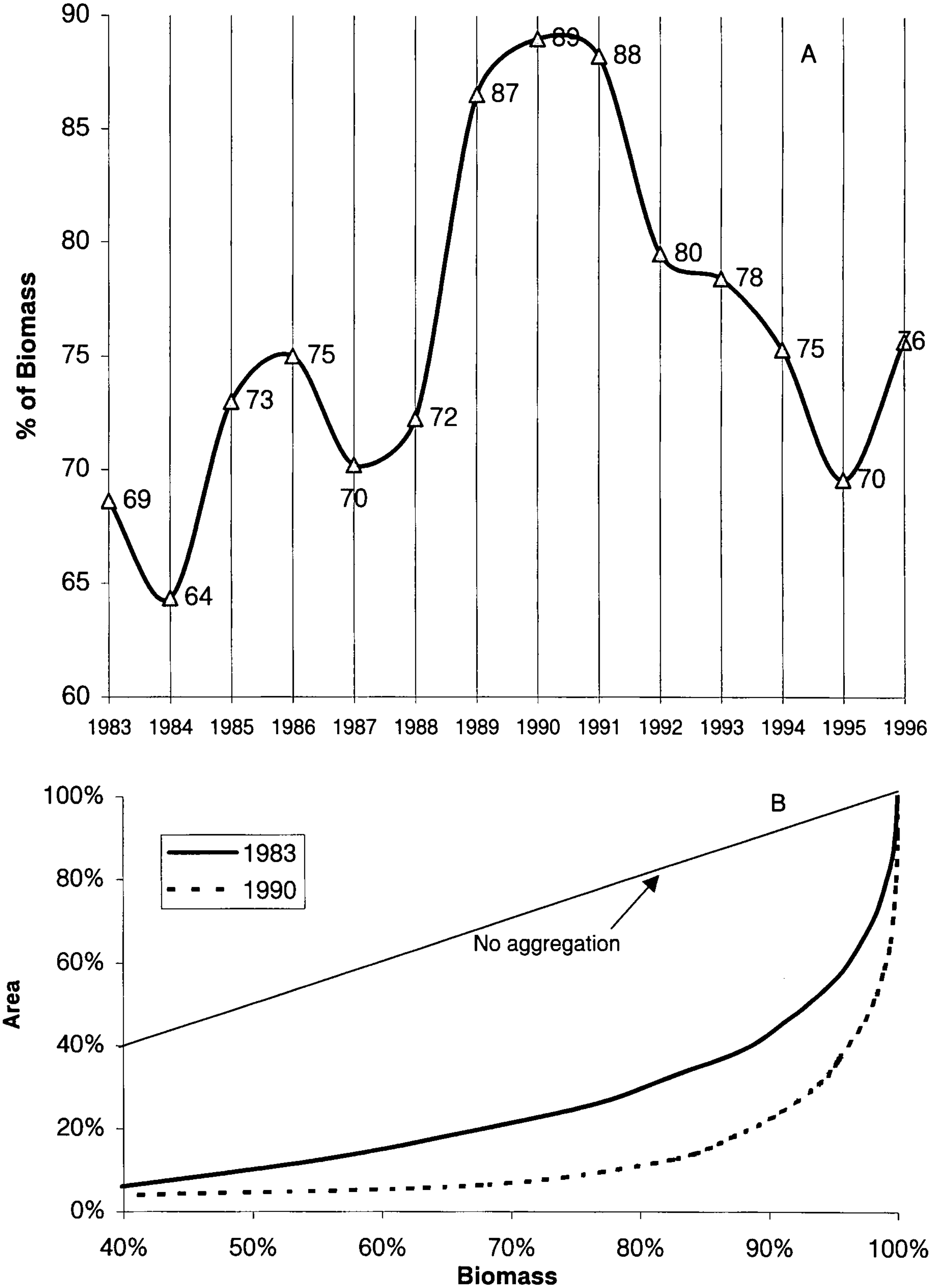

Figure 5 - A. Degree of hyperaggregation of the cod expressed as percent of biomass within 20% of the total area occupied by the cod. B. Relationship between area and biomass in 1983, a"normal" year and 1990 when the cod were hyper-aggregated.

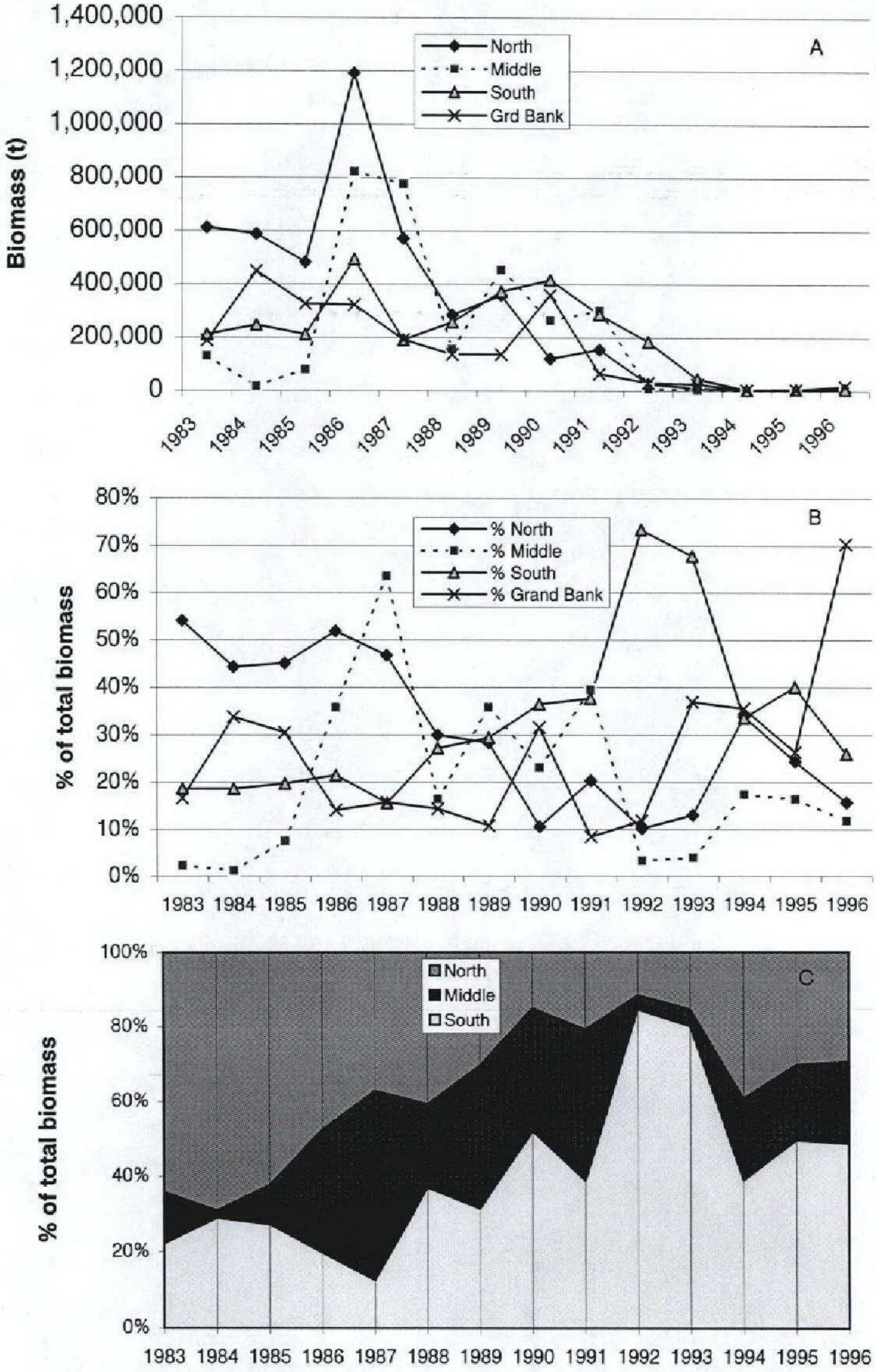

Figure 6 - A. Biomass of northern cod in each of the north, midle, south and Grand Bank areas. B. Percent of biomass in each of the areas. C. Proportion of biomass in the North, Middle and South areas.

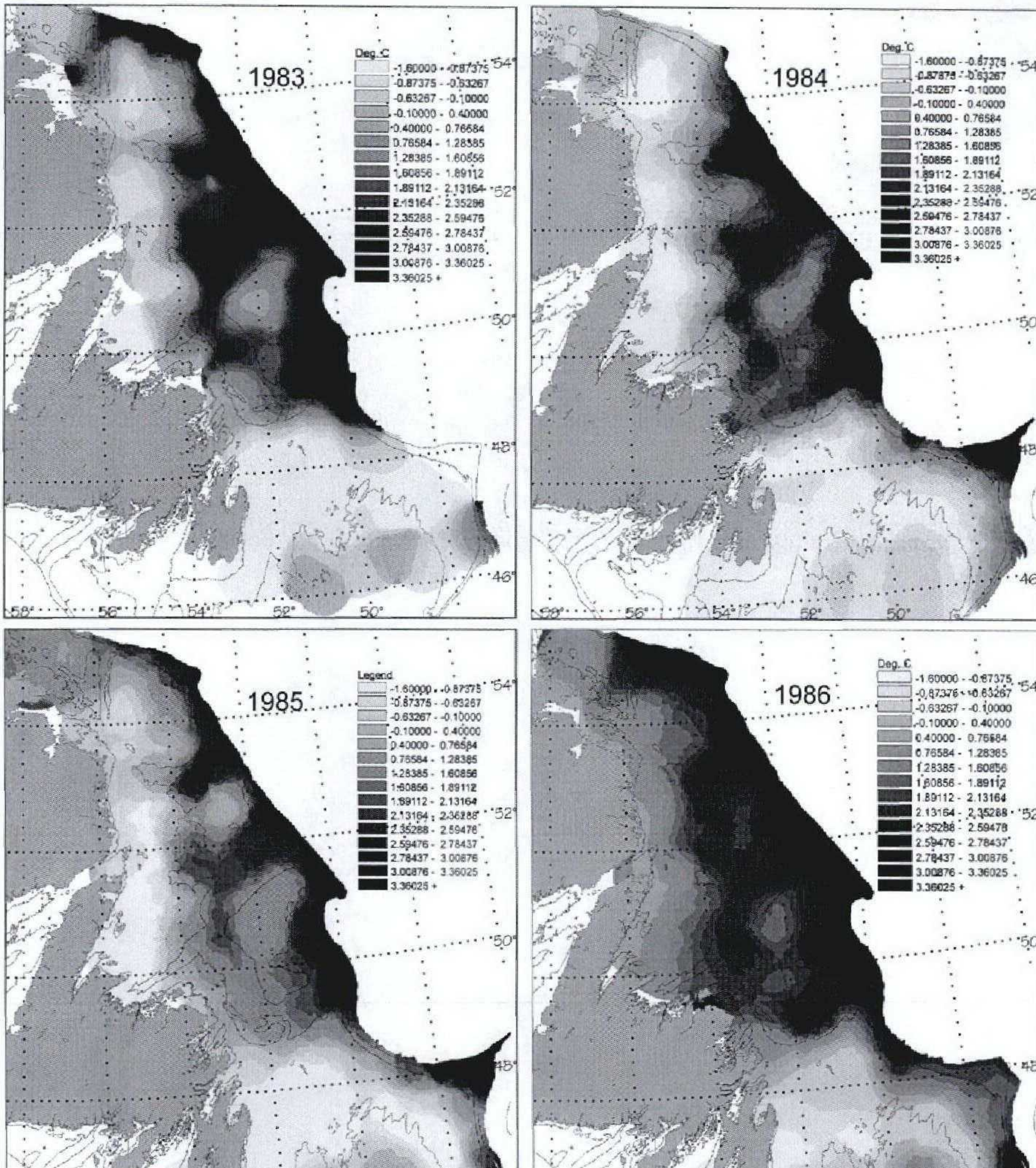

Figure 7a - Changes in the distribution of bottom water temperature as measured during fall research surveys, 1983 to 1986. Grey shades represent levels temperature (Deg. C) as specified in the legend.

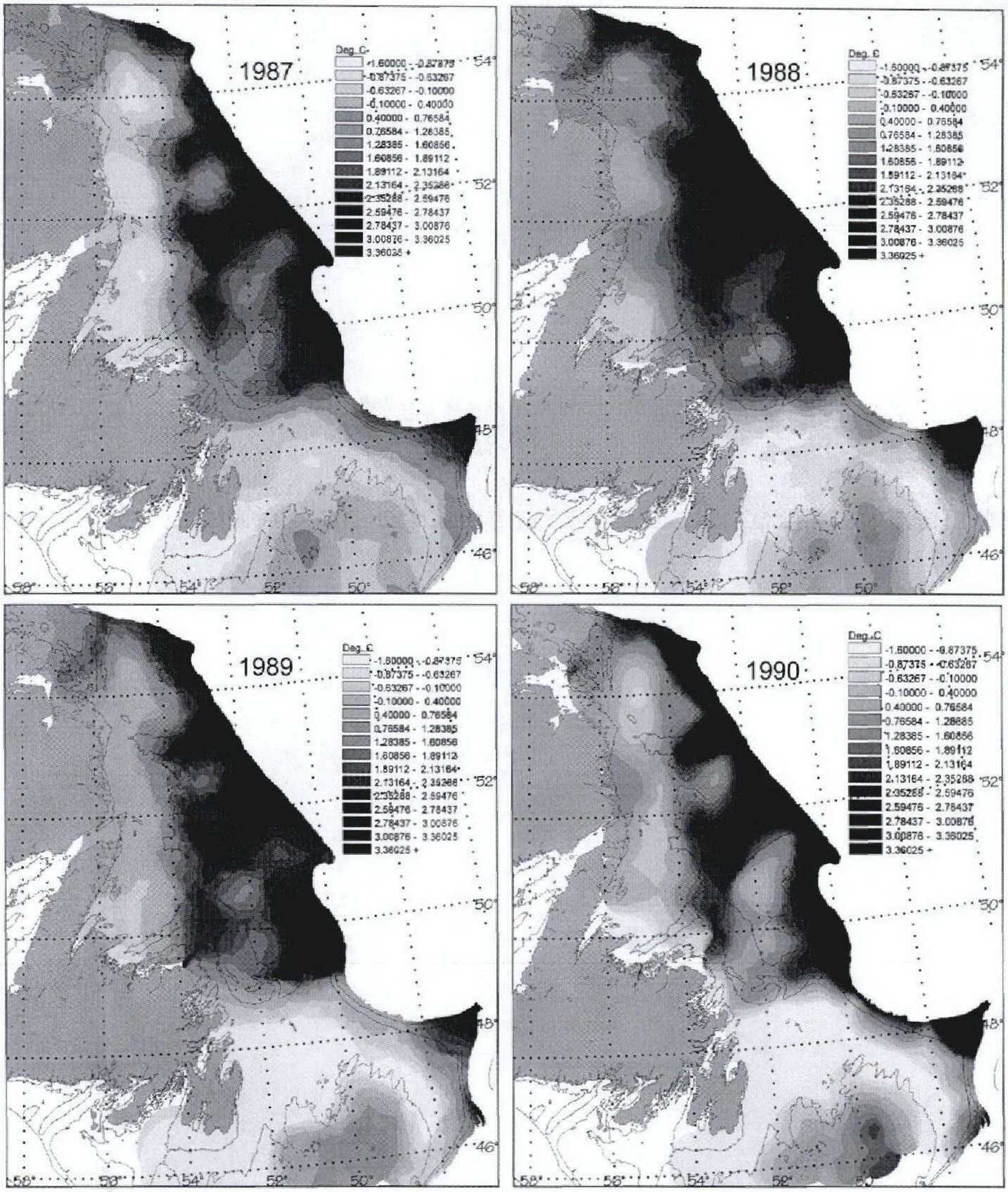

Figure 7b - Changes in the distribution of bottom water temperature as measured during fall research surveys, 1987 to 1990. Grey shades represent levels of temperature (Deg. C) as specified in the legend.

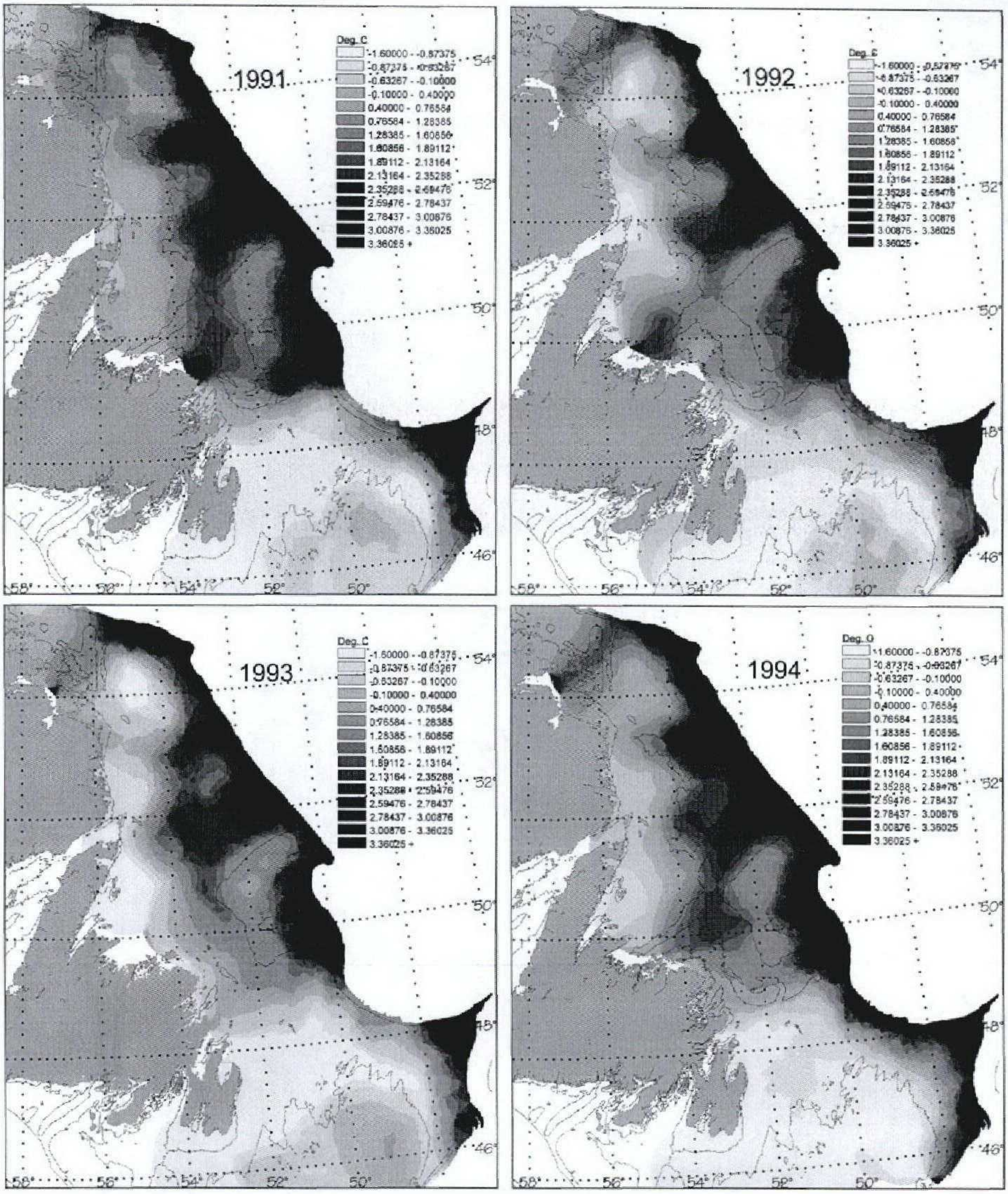

Figure 7c - Changes in the distribution of bottom water temperature as measured during fall research surveys, 1991 to 1994. Grey shades represent levels of temperature (Deg. C) as specified in the legend.

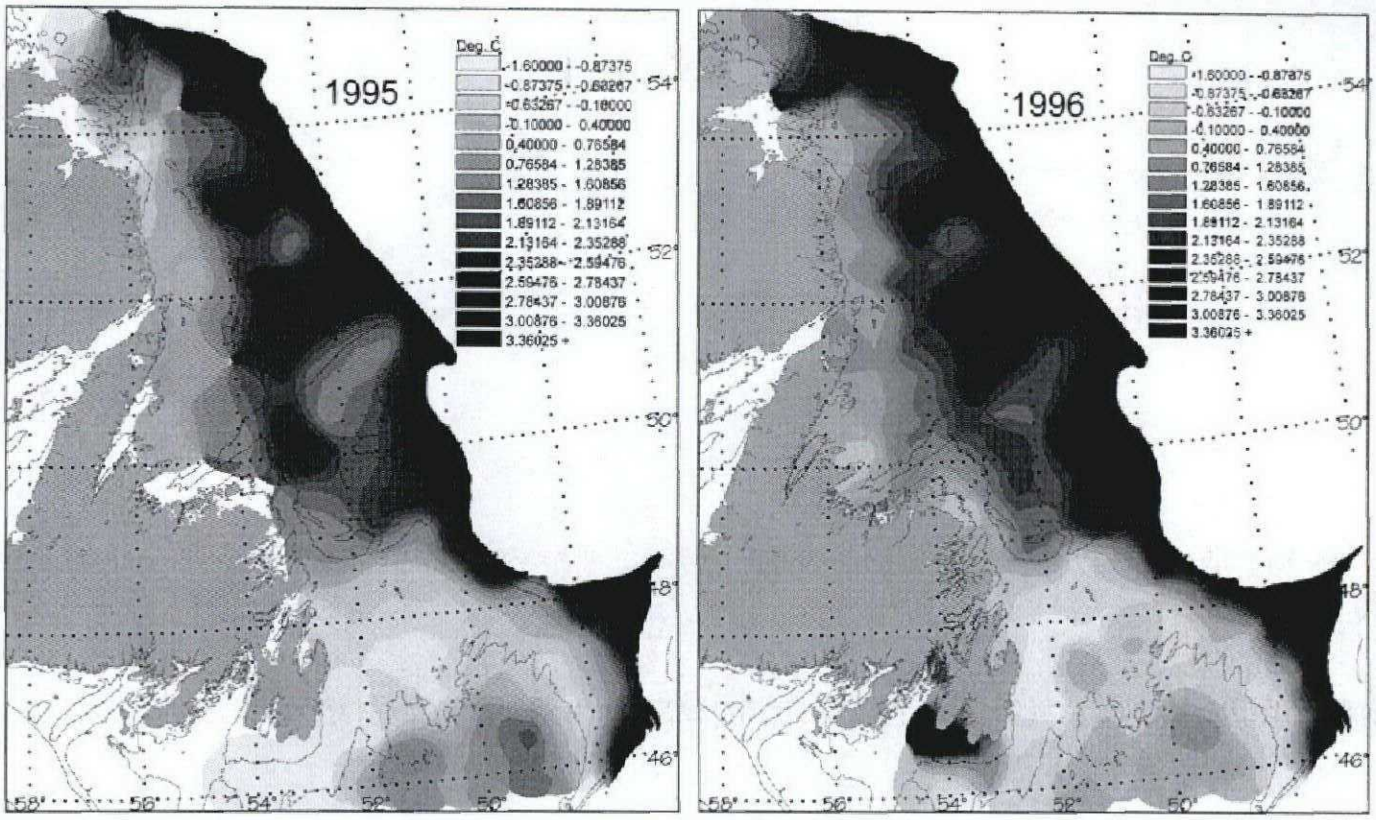

Figure 7d - Changes in the distribution of bottom water temperature as measured during fall research surveys, 1995 to 1996. Grey shades represent levels of temperature (Deg. C) as specified in the legend.

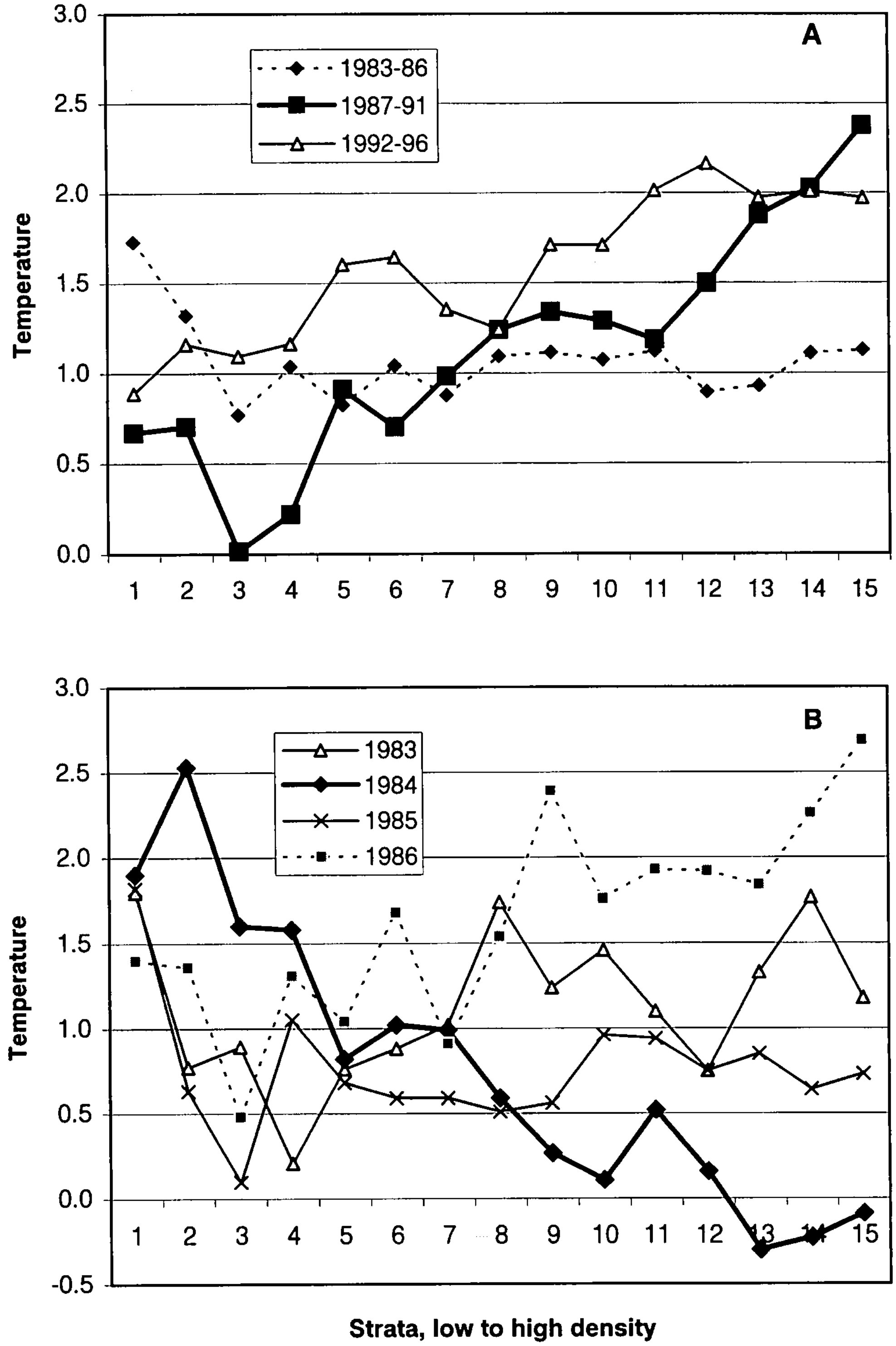

Figure 8 - Average bottom temperature within various cod density strata grouped by various year combinations. Panel A shows 3 year groupings. Panel B consists of annual plots of the first year grouping (1983-86) in Panel A.

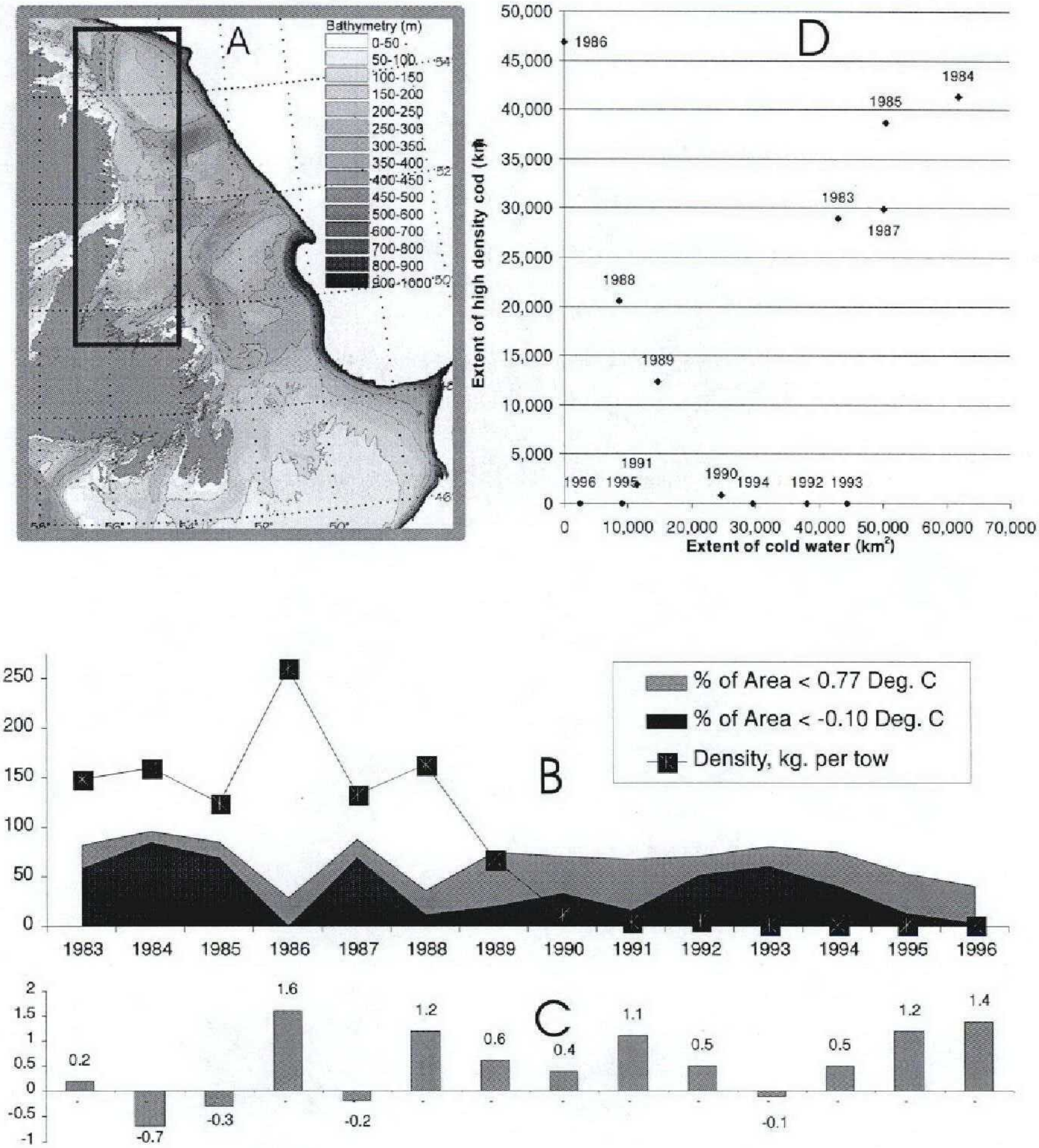

Figure 9 - Cod distribution in relation to bottom temperature within the area most affected by the CIL (cold intermediate layer). A, the top panel, shows the area being analyzed, referred to as the "cold box". B, the middle panel shows the percent of total area within the "cold box" occupied by cold temperatures. This is overlaid by the average density of cod (kg. per tow) within the 'cold box". C, the lowest panel shows average temperature within the "cold box" by year. D, the upper right panel shows the relationship between extent of high density cod (> 100 kg. per two) and extent of the coldest bottom temperature (< -0.1°C) within the box in panel A.