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A Preliminary Investigation of the Effects of Ocean Climate Variations on the Spring Distribution and Abundance of Thorny Skate (*Amblyraja radiata*) in NAFO Divisions 3LNO and Subdivision 3Ps

by

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ABSTRACT

The spatial distributions and abundance of thorny skate are presented in relation to their thermal habitat for NAFO Divisions 3LNO and Subdivision 3Ps during spring surveys from 1971-2003. As reported previously the distribution of thorny skate in this region has undergone significant changes since the early-1980s when they were widely distributed over the entire Grand Banks in all available temperature ranges. The distribution of skates retracted throughout the 1990s and early-2000s with the numbers and total weight per set decreasing in all temperature ranges, but most significantly in temperatures <2°C. On average the most common temperatures where skates were found appear to be in the 3° to 4°C temperature range. The cumulative distributions indicate that on average up to at least the mid-1990s catches rates were distributed across the entire thermal habitat but during the latter half of the 1990s there was an apparent shift towards warmer bottom temperatures. The cumulative frequency distributions based on weight in each temperature bin indicates a preference towards warmer temperatures throughout the time series, particularly during recent years, which may indicate that larger skates prefer the warmer portion of the available habitat. In general, the trend in population of skates both biomass and abundance is associated with changes in the bottom temperatures both at Station 27 and across the Div. 3LNO and Subdiv. 3Ps area, however, after taking into account the change in survey gear in 1996, the response of the population to the warming trend during the latter part of the 1990s is not as great as expected based on earlier periods. While there appears to be a limited response to the warming of the late-1990s, it is clear that ocean temperatures are not the sole factor determining production in this species. It is noteworthy that salinities on the Newfoundland Shelf remained low throughout the 1990s and early-2000s. Changes in shelf stratification arising from variations in salinity likely play a fundamental role in overall ecosystem productivity affecting lower trophic level production and ultimately the food source for many species of marine organisms. Therefore, there are most likely, several possible reasons for the observed changes in the distribution and abundance of thorny skate, including broad scale environmental change and physical and biological interactions between prey species or a shift to a more suitable environment for prey species, in addition to fishery effects.

Introduction

Thorny skate (*Amblyraja radiata* Donovan, 1808, Family Rajidae) is a boreal to arctic species distributed in the north Atlantic. Thorny skate have undergone a decline over it western Atlantic entire range but the reasons for that decline are unclear (Kulka and Miri, 2003). As well, the same authors reported a substantial change in the distribution of thorny skate starting in the mid-1980s .Thorny skate, formerly inhabiting nearly the entire Grand Banks are now largely concentrated along the southwest slope and into the slope of the Laurentian Channel. Mortality due to fishing clearly played a role in the decline but the northern Grand Banks where much of the decline took place corresponds to a region that is seldom fished. It has however, the coldest bottom waters on the Grand Banks (Colbourne, 2003).

Kulka and Mowbray (1998) compared cumulative area and biomass in relation to ambient temperature and their results indicated seasonal differences with neither spring nor fall distributions of skate thermal neutral. The densest aggregations were found on the warmer sections of the Banks. In spring, the percent of biomass was far below the percent of available habitat over almost the entire temperature range, indicating a strong association with the warmest waters. In addition skate appeared to preferentially distribute in warmer waters on the Grand Banks in spring compared to the fall months. In this manuscript we present an analysis of the distribution and abundance of thorny skate in relation to their thermal habitat in NAFO Div. 3LNO and Subdiv. 3Ps for the spring surveys. We begin by re-examining the mean catch rates and the cumulative distributions of available temperature to the survey and catch numbers and weights for the complete range of temperatures encountered in the region. Trends in the ocean climate are then compared to recent changes in the biomass and abundance of thorny skate. Finally the spatial distribution maps of thorny skate catch rates in relation to the near-bottom temperature fields for the spring surveys are presented.

Data and Methods

Canada has been conducting stratified random groundfish trawl surveys in NAFO Div. 3LNO and Subdiv. 3Ps since 1971. Each division was stratified based on the depth contours from available standard navigation charts (Fig. 1). Areas within each division, within a selected depth range, were divided into strata and the number of fishing stations in each stratum was allocated based on an area weighted proportional allocation (Doubleday, 1981). The stratification scheme is constantly being revised as more accurate navigation charts become available and efforts are being made to extend the stratification scheme shoreward and into deeper water along the shelf edge (Bishop, 1994; Murphy, 1996; Brodie, 1996). Bottom temperatures and data on thorny skate are routinely collected during all ground fish surveys. During the fall of 1995 the Canadian research vessel surveys in the Newfoundland and Labrador Region changed survey trawls from an Engles 145 to a Campelen 1800 shrimp trawl (McCallum and Walsh, 1996).

The historical oceanographic data set for the Newfoundland and Labrador Shelf is available from archives at the Marine Environmental Data Service (MEDS) in Ottawa and from databases maintained at the Bedford Institute of Oceanography in Dartmouth, Nova Scotia and at the Northwest Atlantic Fisheries Centre in St. John's Newfoundland. Since 1989, net-mounted conductivity-temperature-depth (Seabird model SBE-19 CTD systems) recorders have replaced XBTs on the annual assessment surveys as the primary oceanographic instrument. This system records temperature and salinity data during trawl deployment and recovery and for the duration of the fishing tow. Data from the net-mounted CTDs are not field calibrated, but are checked and factory calibrated periodically maintaining an accuracy of 0.005^{o}C in temperature and 0.005 in salinity. Expendable bathythermographs (XBTs) are only used when the net-mounted CTD fails during the tow, these are accurate to within 0.1^{o}C.

Data on thorny skate abundance and distribution were available for the years 1971-2003 for the spring surveys. Fishing sets of 15 minute duration at a towing speed of 3 knots were randomly allocated to strata covering the most of the 3PLNO area to a depth of 1 500 m (Fig. 1) (Brodie, 1996; McCallum and Walsh, 1996). There was a change in survey gear after the spring 1995 survey from an Engels 145 groundfish trawl to a Campelen 1800 shrimp trawl. The implications and conversion factors to account for this change are discussed in Kulka and Miri (2003). The STRAP2 (Smith and Somerton, 1981) estimates of biomass and abundance of skates provided by Kulka and Miri (2003) were used to examine long-term trends in relation to the environment. The mean numbers and weight of skates for all sets within 1^{o}C-temperature bins for each survey were computed for the period 1975-2002 representing the average, 1984-1989, 1990-1995 a cold period, 1998-2001 a warm period and for individual years. Cumulative frequency distributions of catch numbers for each temperature bin are compared to the available temperature distribution within the 3LNO and 3Ps region for all surveys. For the purpose of this preliminary analysis, these distributions were not weighted by sampling intensity or stratum area. Near-bottom temperature grids for NAFO Div. 3LNO and Subdiv. 3Ps were then produced from all available data collected during the spring for the years 1975-2003. All near-bottom temperature values for the period of each survey were interpolated onto a regular grid and contoured using a geostatistical (2-dimensional Kriging) procedure. The numbers of skate per fishing set are displayed over the temperature contours as expanding solid circles proportional to the magnitude of the catch.

Results

The average number and weight of skates caught per fishing set in 1°C-temperature bins are displayed in Fig. 2, 3 and 4 for the spring surveys. It appears that in this region skates are found in temperatures ranging from <-1°C to >8°C, i.e. all temperature encountered in this region. However, significantly higher numbers and weight of skates were caught in the 3° to 5°C temperature range with much lower numbers in the -1° to 2°C temperature range. Occasionally, some sets in areas of the southern portions of 3NOP in slope water with temperatures >6°C contained very high numbers of skate. The time series shown in Fig. 2 and the distributions for individual years and periods (Fig. 3 and 4) indicates that the distribution of skates in the various temperature bins were reasonably consistent from 1975 up to the late-1980s. Beginning in the early-1990s however, the numbers and total weight per set decreased in all temperature ranges but most significantly in temperatures <2°C. On average (Fig. 3 and 4 top left panels) the most common bottom temperatures where skates were found appear to be in the 3° to 4°C temperature range. These temperatures are found all along the slopes of the Grand Banks from northern 3L to 3Ps. In addition, as mention above some sets in waters with temperatures >6°C contained very large numbers of skates. For example, in 2002 the highest numbers and weight appear to be in the 7° to 8°C temperature range. This was the result of two sets near the southeast corner of St. Pierre Bank which contained 126 and 167 skates. Near bottom temperatures >4°C during the spring are only found in the southern portions of Div. 3O and Subdiv. 3Ps. A similar set in 1997 in the same area contained 252 skates.

To further partition the thermal habitat of skates in NAFO Div. 3LNO and Subdiv. 3Ps we computed annual and average cumulative catch numbers and weight temperature distributions based on data from the spring surveys for different periods (Fig. 5 and 6). The cumulative frequency distribution of the number of sets for each temperature bin shows the temperature available to the survey and the cumulative distributions of catch numbers and weight show the distribution of catches in relation to the available temperature. These results indicate that on average up to at least the mid-1990s, catches were distributed across the entire thermal habitat (Fig. 5 top panels). Towards the end of the decade of the 1990s however, there was an apparent shift in the catch number distributions towards warmer bottom temperatures. In 2002 for example, there were less than 10% of the catch in <0°C water with about 30% of the sets in this water temperature whereas in the earlier part of the 1990s about 45% of the catch numbers and about 50% of the sets were in <0°C water. Also in the late-1990s and early-2000s catches were absent in the coldest water where temperatures were <-1°C. In spite of some sets with very large catches in waters >5°C only about 10-20% of the total numbers are found in these waters. The cumulative frequency distributions for the weight of skates found in each temperature bin indicates a preference towards warmer temperatures throughout the time series and particularly during recent years (Fig. 6). This may indicate that larger skates prefer the warmer portion of the available habitat. In 2001 for example, 50-60% of the biomass was associated with bottom temperatures >3°C, while only 20-30% of the available sets were in temperatures >3°C.

Ocean temperature and salinity have been measured routinely since 1946 at a standard hydrographic monitoring station (Station 27) located in the inshore branch of the Labrador Current on the Newfoundland Continental Shelf (Colbourne and Fitzpatrick, 1994). Bottom temperatures (176 m) at this site were below normal during the early-1970s but increased to above normal values from 1975 to 1982. After 1982 they remained below normal until 1996, the longest time period of below normal temperatures in the 50-year record (Fig. 7). The spring research survey biomass and abundance indices derived using STRAP2 are also displayed in Fig. 7 without any corrections for the change of survey trawl in 1996. Also data for 1983 was not included since only the 3Ps area was surveyed. These indices show large changes in the relative population size over the time series. It appears that relative biomass after increasing during the 1970s and early-1980s declined rapidly from the mid-1980s reaching a minimum level by 1995. In general the trend in population of skates, both biomass and abundance, is associated with the changes in the bottom temperatures at Station 27 (Fig. 7). If we apply the conversion factor to the population indices and present the time series as Campelen trawl equivalents, the general association between bottom temperatures is still evident, however the response of the population to the warming trend since 1996 is not as great as expected based on earlier associations (Fig. 8).

All available oceanographic data in the 3PLNO area were gridded for the spring period of each year at a spatial resolution of approximately 100 km^2 or approximately 0.1° latitude by 0.1° longitude. A mean bottom temperature for each grid element was calculated and the overall average computed to produce an annual time series of the spatially averaged bottom temperature for the region. The time series exhibits very high variability prior to the mid-1980s with mean temperatures in the 2° to 3°C range. After the mid-1980s bottom temperatures declined significantly reaching minimum values in the early-1990s. Throughout the latter part of the 1990s temperatures began to increase reaching maximum values by 1999 and 2000 before decreasing again in 2001 and 2002. There is a weak association between bottom temperatures and the trend in biomass and abundance of skates particularly during the past decade (Fig. 9). Again however the response of the population to the warming during the latter part of the 1990s is not as great as expected after taking into account the change in survey trawl during the spring of 1996 (Fig. 10).

Salinities on the Newfoundland and Labrador Shelf have also experienced sharp annual fluctuations and long-term trends over the past 3 decades. Unlike other decades however salinities on the Newfoundland Shelf have remained low throughout the 1990s and early-2000s potentially as a result of Arctic warming and the subsequent increase in ice melt. Ignoring the anomalous high and low values of 1976 and 1983 there appears to be a significant correlation between the Campelen equivalent estimated biomass and the trend in the vertically averaged salinity at Station 27 (Fig. 11).

As reported by Kulka and Miri (2003) the distribution of thorny skate in this region has undergone significant changes since the early-1980s. In the early-1980s skates were widely distributed over the entire Grand Banks in all available temperature ranges. By the late-1980s and early-1990s many areas of the Grand Bank were devoid of skates with the higher concentration found in deeper waters along the slopes of the banks. The distribution of skates retracted even further throughout the 1990s and early-2000s.

The spring bottom temperature maps together with the number of skates caught per set for NAFO Div. 3LNO and Subdiv. 3Ps are displayed in Fig. 12. In general, spring bottom temperatures in the northern areas ranged from <0^{o}C in the inshore regions of the Avalon Channel to >3^{o}C at the shelf edge. Over the central and southern areas bottom temperatures ranged from 1^{o}C to >3.5^{o}C on the Southeast Shoal and >3^{o}C along the edge of the Grand Bank. During the cold years from 1990-1995 virtually the entire 3L area (except the deeper slope regions) and a significant portion of 3NO was covered by <0^{o}C water (Colbourne and Fitzpatrick, 2003). Beginning around 1996 the area of <0^{o}C water began to retract and by 1999 it was restricted to a small area in the Avalon Channel. During 2001 and 2003 the area of <0^{o}C water began to increase again covering most of the plateau of the Grand Bank in Div. 3L. Near-bottom temperatures in the deeper slope regions undergo considerable annual variability but do not exhibit any significant trend.

The number of skates caught per fishing set during each survey is displayed with the temperature contours in Fig. 12 for the spring surveys as expanding symbols. The size of the circle is proportional to the magnitude of the catch in each set. The majority of fishing sets in the shallow regions (water depths <100-m) of southern 3L and northern 3NO show either zero catches or very low numbers. During the spring surveys most of the large catches were from the warmer water along the slopes of Div. 3LNO and Subdiv. 3Ps with particularly large catches in the warm slope water of southern most regions. In division 3N and the eastern regions of 3L there were many large catches in all temperature ranges up at least until 1993. Since then however, catches have been decreasing in most areas of the Grand Banks with the number of zero catch rates increasing significantly throughout the 1990s and up to 2003. Although there were some zero catches in the warm slope waters during most years the surveys in general continue to show relatively large catch rates throughout the 1990s and up to 2003 mainly in the 3^{o}C to 4^{o}C temperature range and a few very large catches in temperatures >6^{o}C.

Summary and Conclusions

As reported previously, the distribution of thorny skate in this region has undergone significant changes since the early-1980s when they were widely distributed over the entire Grand Banks in all available temperature ranges. By the late-980s and early-990s however, many areas of the Grand Bank were devoid of skates with the higher concentration found in deeper waters along the slopes of the banks. The distribution of skates retracted even further throughout the 1990s and early-000s with the numbers and total weight per set decreasing in all temperature ranges but most significantly in temperatures <2^{o}C. On average the most common temperatures where skates were found appeared to be in the 3^{o} to 4^{o}C range. The cumulative distributions indicate that on average, up to at least the mid-1990s, catches were distributed across the entire thermal habitat but towards the end of the decade of the 1990s there was an apparent shift in the catch number distributions towards warmer temperatures. The cumulative frequency distributions based on weight of skates caught in each temperature bin indicates a preference towards warmer temperatures throughout the time series and particularly during recent years, which may indicate that larger skates prefer the warmer portion of the available habitat. In general, the trend in population of skates, both biomass and abundance, is associated with the changes in bottom temperatures both at Station 27 and across the NAFO Div. 3LNO and Subdiv. 3Ps area. However, after taking into account the survey gear change in 1996 the response of the population to the warming trend since 1996 is not as significant as expected based on earlier periods.

The waters off Newfoundland and Labrador are a habitat to many overlapping Arctic and boreal marine species including thorny skates. Therefore, variations in the thermal habitat are likely an important physical variable influencing production in many species of marine organisms in this region. Ocean climate in the northwest Atlantic, particularly on the Newfoundland Continental Shelf (NAFO Subareas 3) during the recent past has experienced sharp annual fluctuations, decadal oscillations and longer-term trends over several decades (Colbourne, 2004). In particular, the decade of the 1990s has experienced some of the most dramatic variations since measurements began during the mid-1940s. It is clear that major changes have taken place in the population dynamics of thorny skate on the Grand Banks of Newfoundland during this period particularly during the late-1980s and 1990s. Coincident with these climate variations many other marine species have also shown dramatic changes in abundance and distribution during the same period (Carscadden *et al*., 2001, Lilly *et al*., 1999, Colbourne and Anderson, 2003). While there appears to be a limited response to the warming of the late-1990s it is clear that ocean temperatures are not the sole factor determining production in this species. It is also noteworthy that salinities on the Newfoundland Shelf remained below normal throughout the 1990s and early-2000s. Changes in shelf stratification arising from variations in salinity likely plays a fundamental role in overall ecosystem productivity, affecting lower trophic level production and ultimately the food source for many species of marine organisms. Therefore, there are most likely several possible reasons for the observed changes in the distribution and abundance of thorny skate including interactions between physical and biological factors such as an increase in prey species or a shift to a more suitable environment for prey species. Finally, although the numbers of skate from the 1971-1995 surveys have been converted to equivalent Campelen trawl units there may also be some residual effects remaining in the series, which may contribute to the overall trends.

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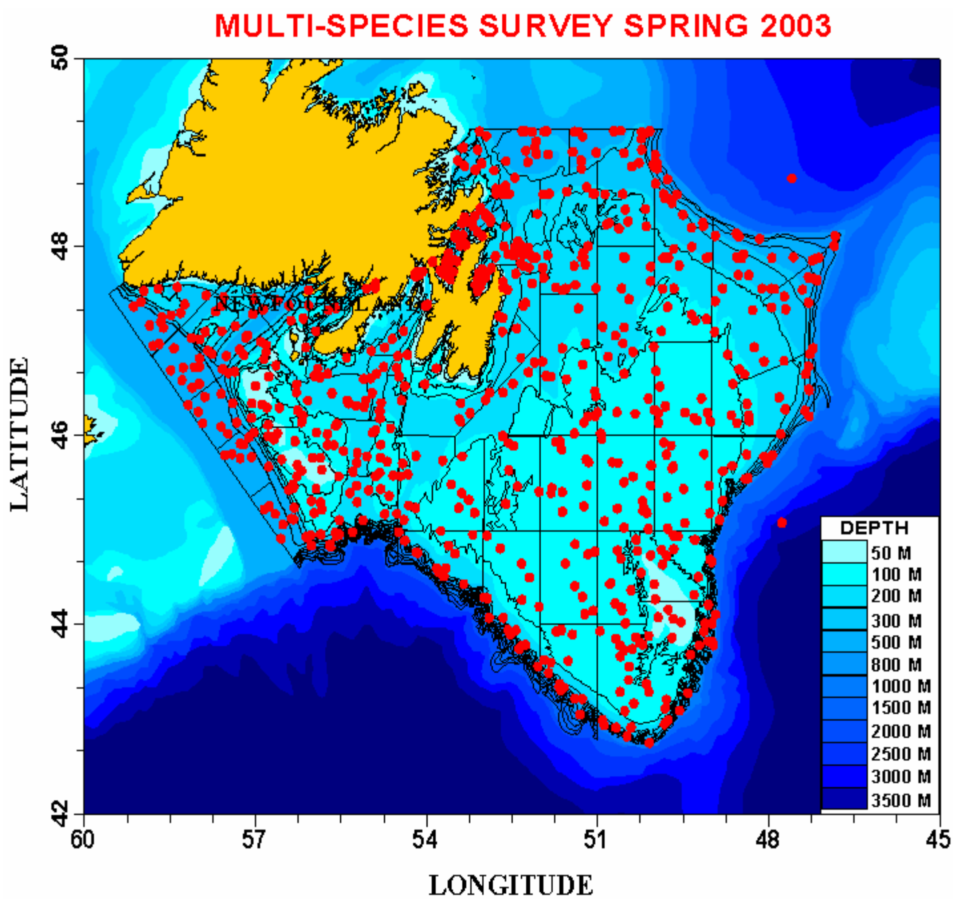


Fig. 1 Location map showing the stratified area and the positions of fishing sets during the Canadian research trawl survey in NAFO Div. 3LNO and Subdiv. 3Ps during the spring of 2003.

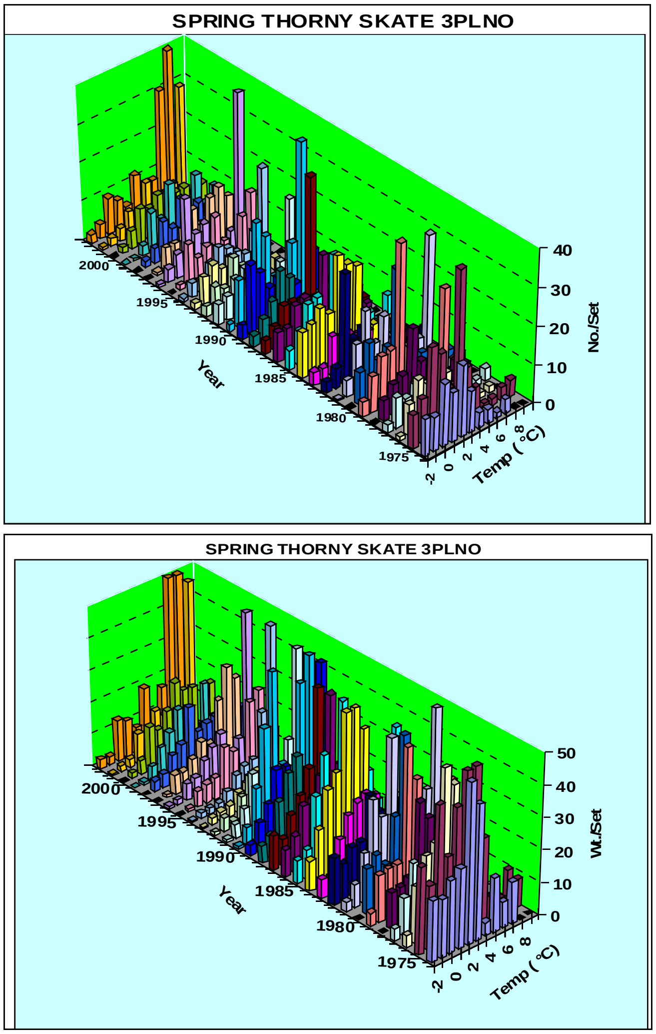


Fig. 2. The average number (top panel) and weight (bottom panel) of thorny skate per fishing set in 1°C temperature bins for the spring surveys in NAFO Div. 3LNO and Subdiv. 3Ps for the years 1975-2003.

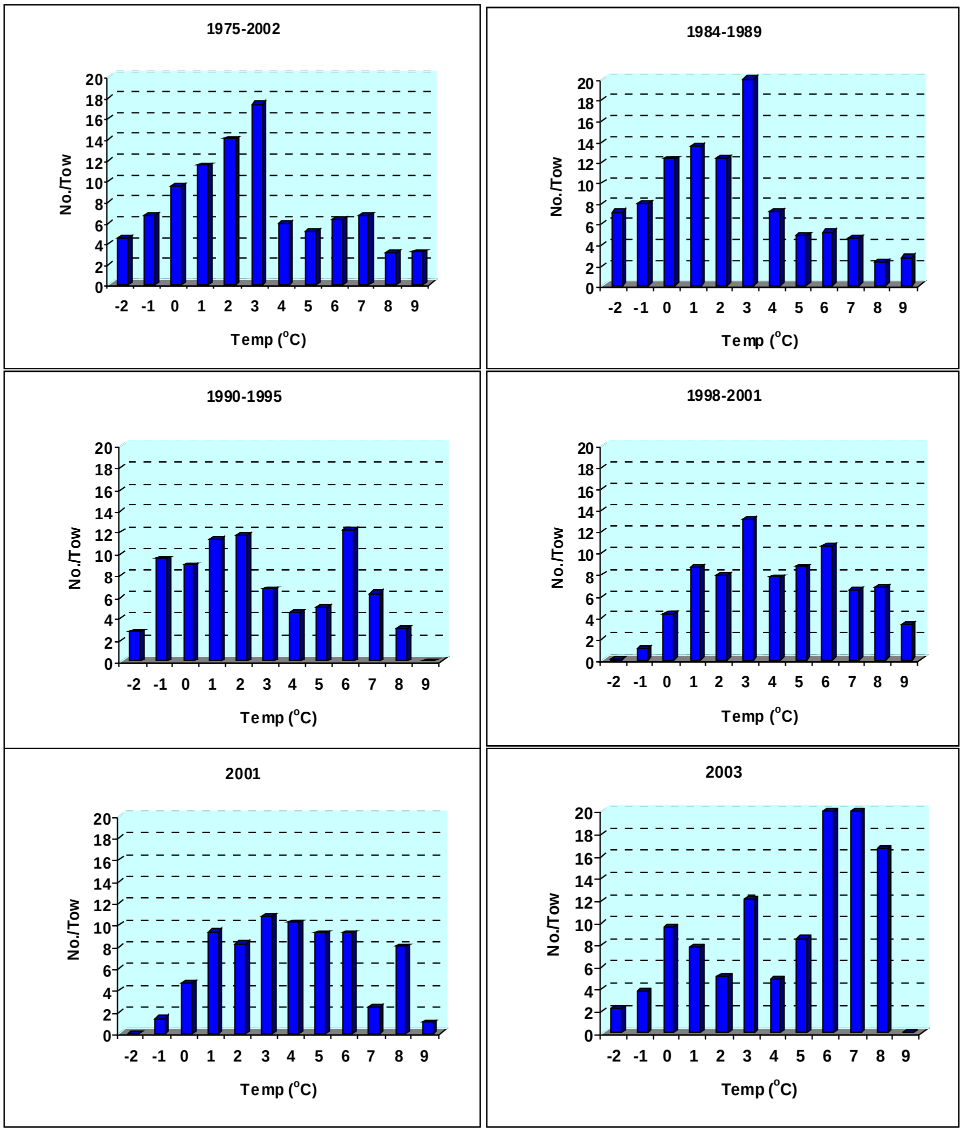


Fig. 3. The average number of thorny skate per fishing set in 1°C temperature bins for the spring surveys in NAFO Div. 3LNO and Subdiv. 3Ps for individual years and periods corresponding to different climate regimes.

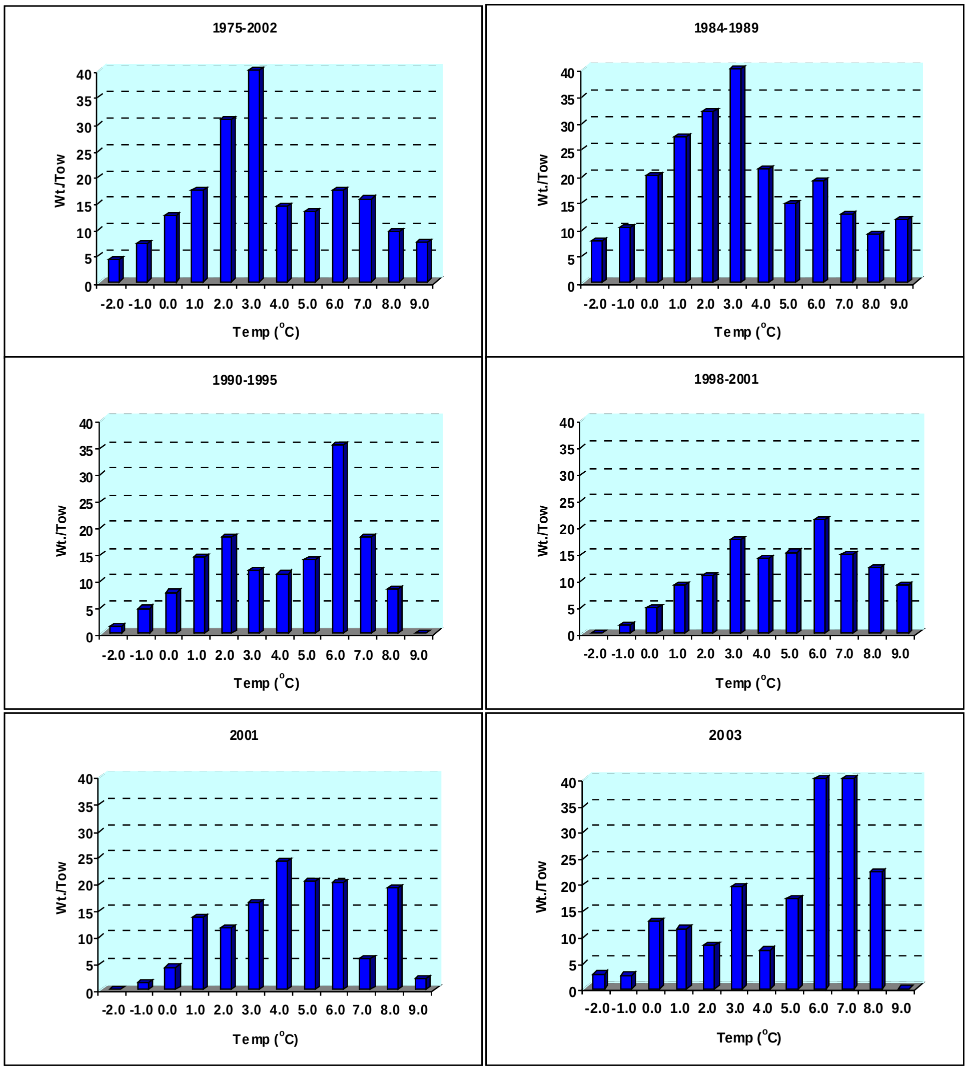


Fig. 4. The average weight of thorny skate per fishing set in 1°C temperature bins for the spring surveys in NAFO Div. 3LNO and Subdiv. 3Ps for individual years and periods corresponding to different climate regimes.

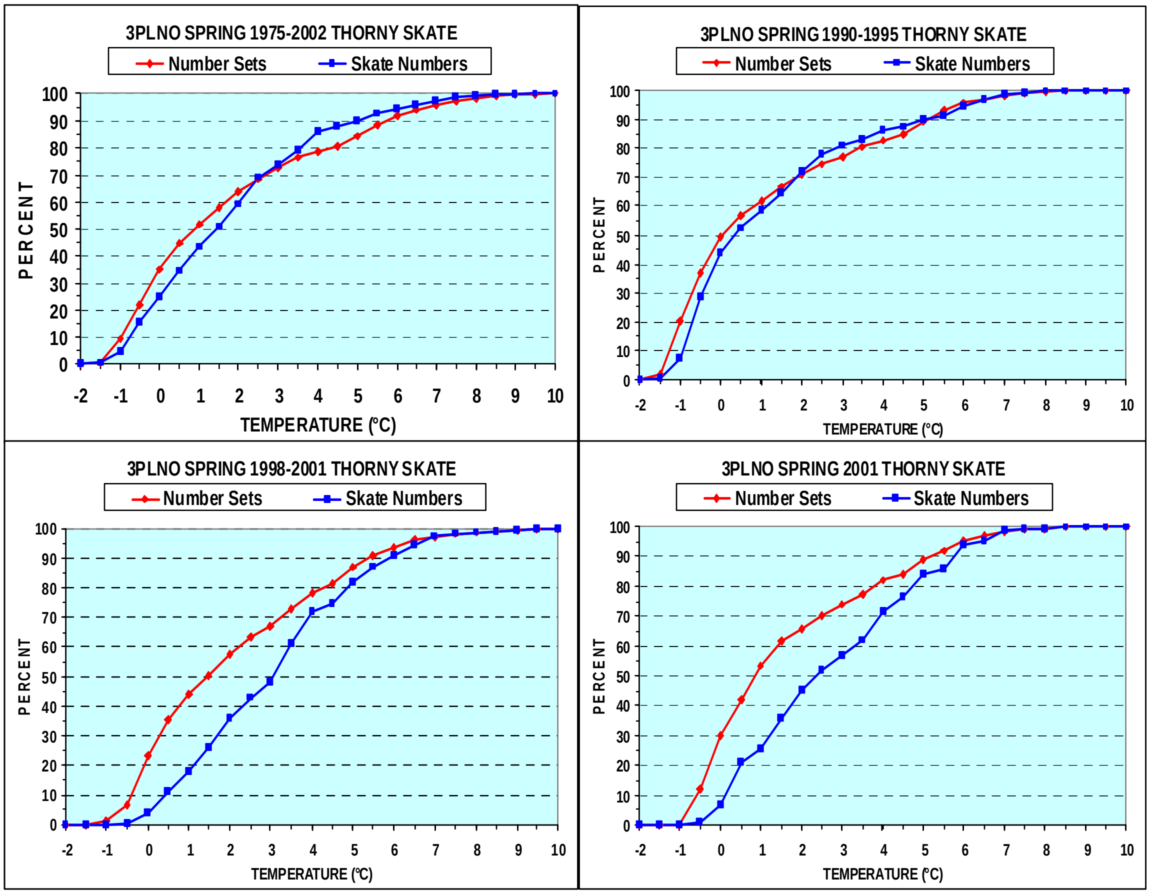


Fig. 5. Cumulative frequency distributions of the number of sets in the 3PLNO survey in 0.5°C temperature bins and the cumulative frequency distribution of the number of skate caught in 0.5°C temperature bins for the spring surveys for different periods and years corresponding to different climate regimes.

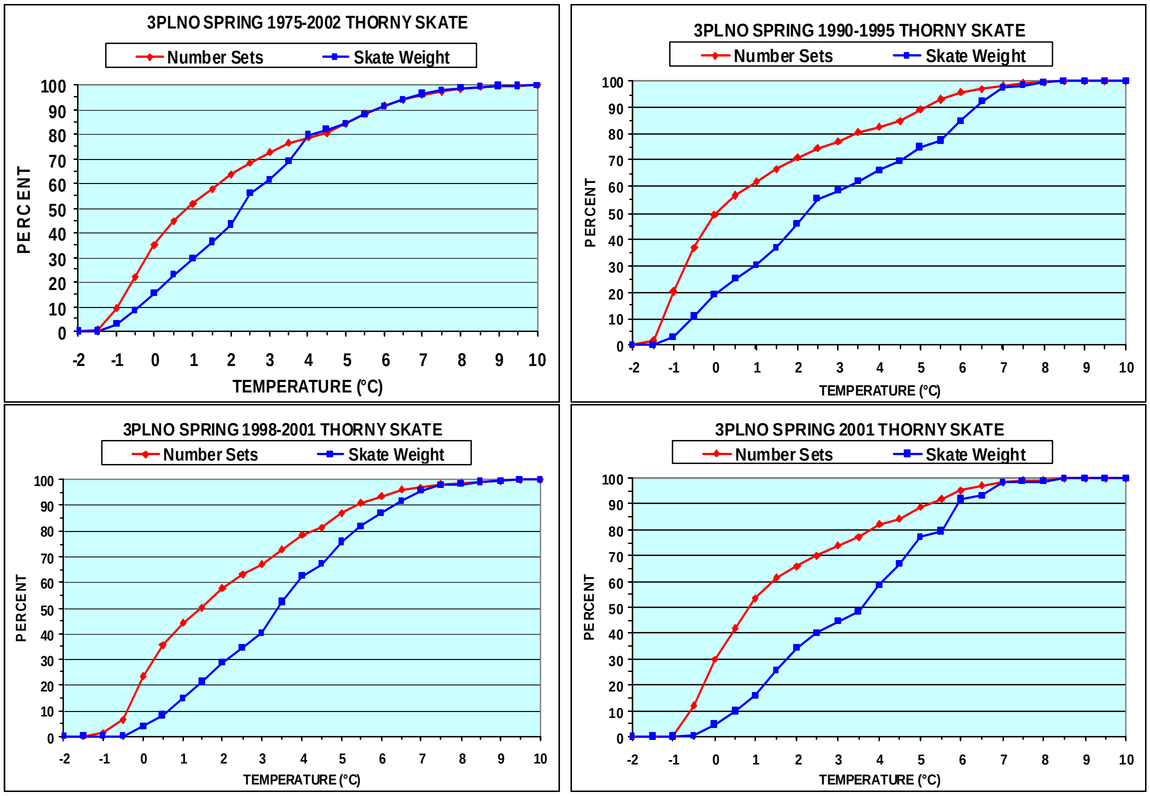


Fig. 6. Cumulative frequency distributions of the number of sets in the 3PLNO survey in 0.5°C temperature bins and the cumulative frequency distribution of the total weight of skate caught in 0.5°C temperature bins for the spring surveys for different periods and years corresponding to different climate regimes.

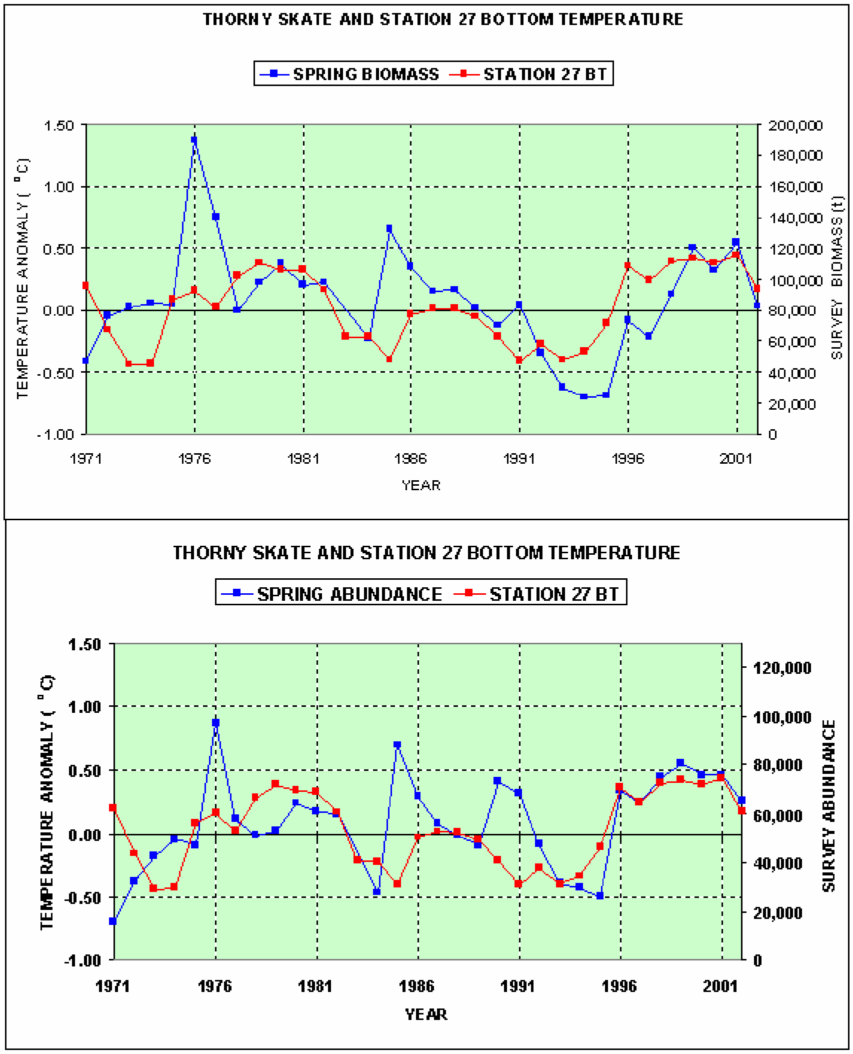


Fig. 7. Spring survey relative biomass and abundance indices for thorny skate in NAFO Div. 3LNO and Subdiv. 3Ps for 1971-2002 together with the Station 27 bottom temperature anomaly.

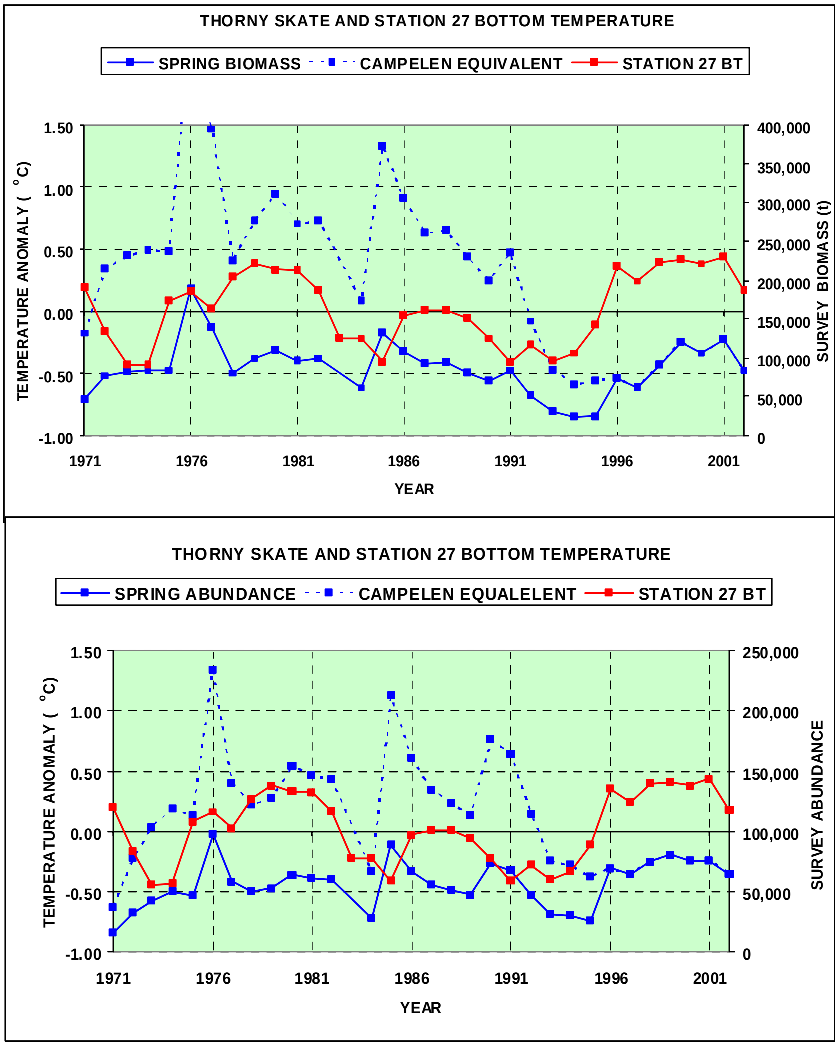
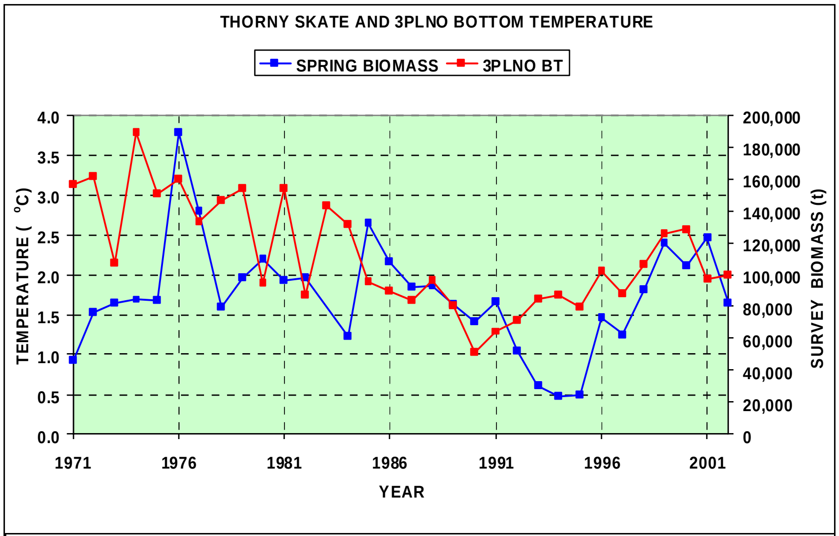


Fig. 8. Spring survey relative biomass and abundance indices for thorny skate including the campelen equivalents of the Engles estimates in NAFO Div. 3LNO and Subdiv. 3Ps for 1971-2002 together with the Station 27 bottom temperature anomaly.



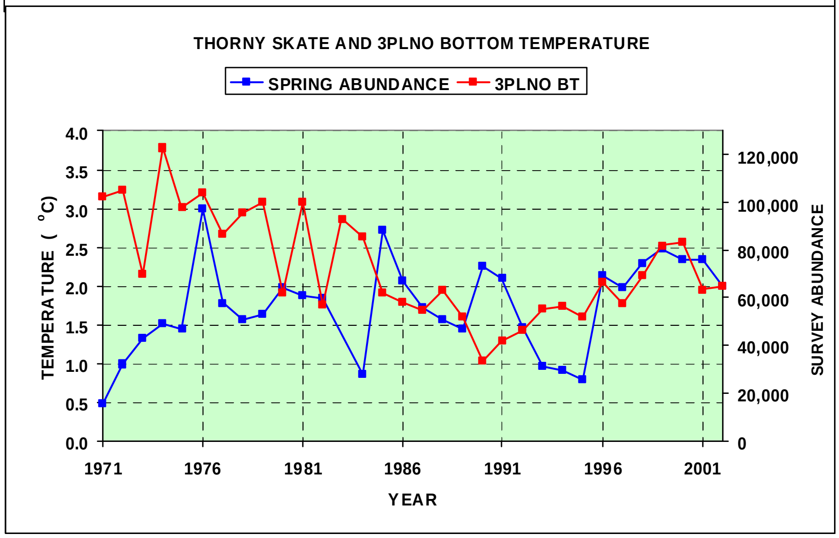


Fig. 9. Spring survey relative biomass and abundance indices for thorny skate in NAFO Div. 3LNO and Subdiv. 3Ps for 1971-2002 together with the spatially averages 3PLNO bottom temperature.

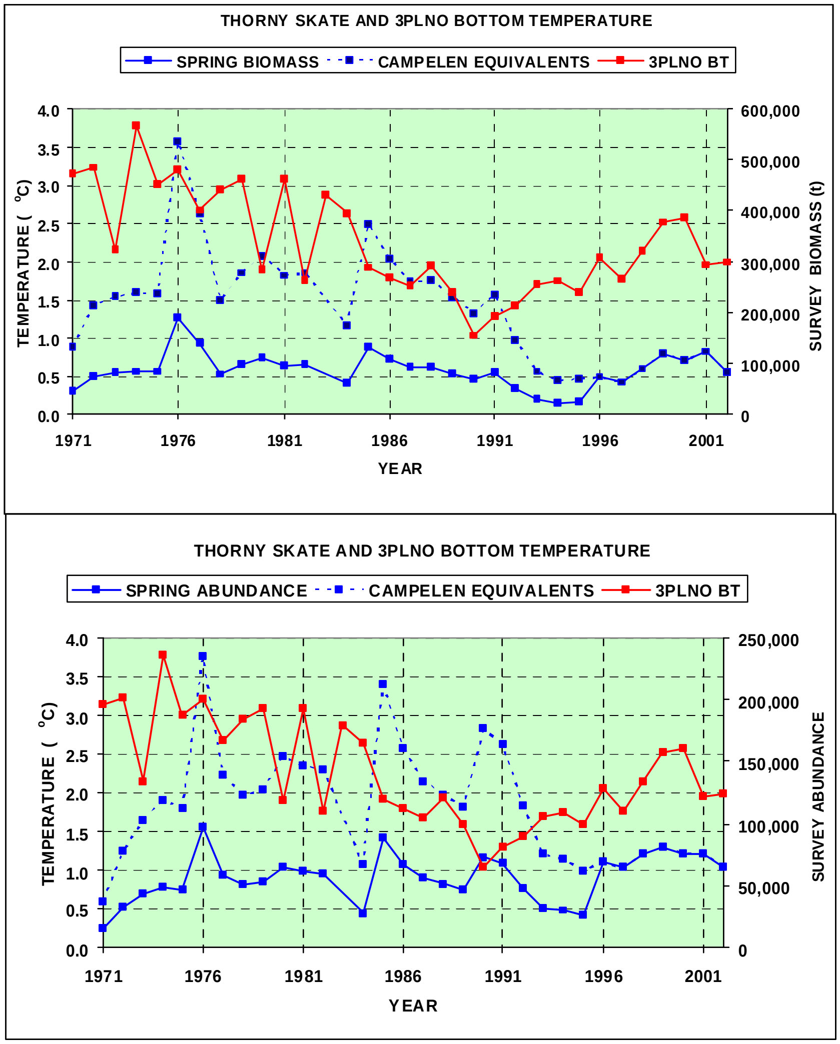


Fig. 10. Spring survey relative biomass and abundance indices for thorny skate including the campelen equivalents of the Engles estimates in NAFO Div. 3LNO and Subdiv. 3Ps for 1971-2002 together with the spatially averaged 3PLNO bottom temperature.

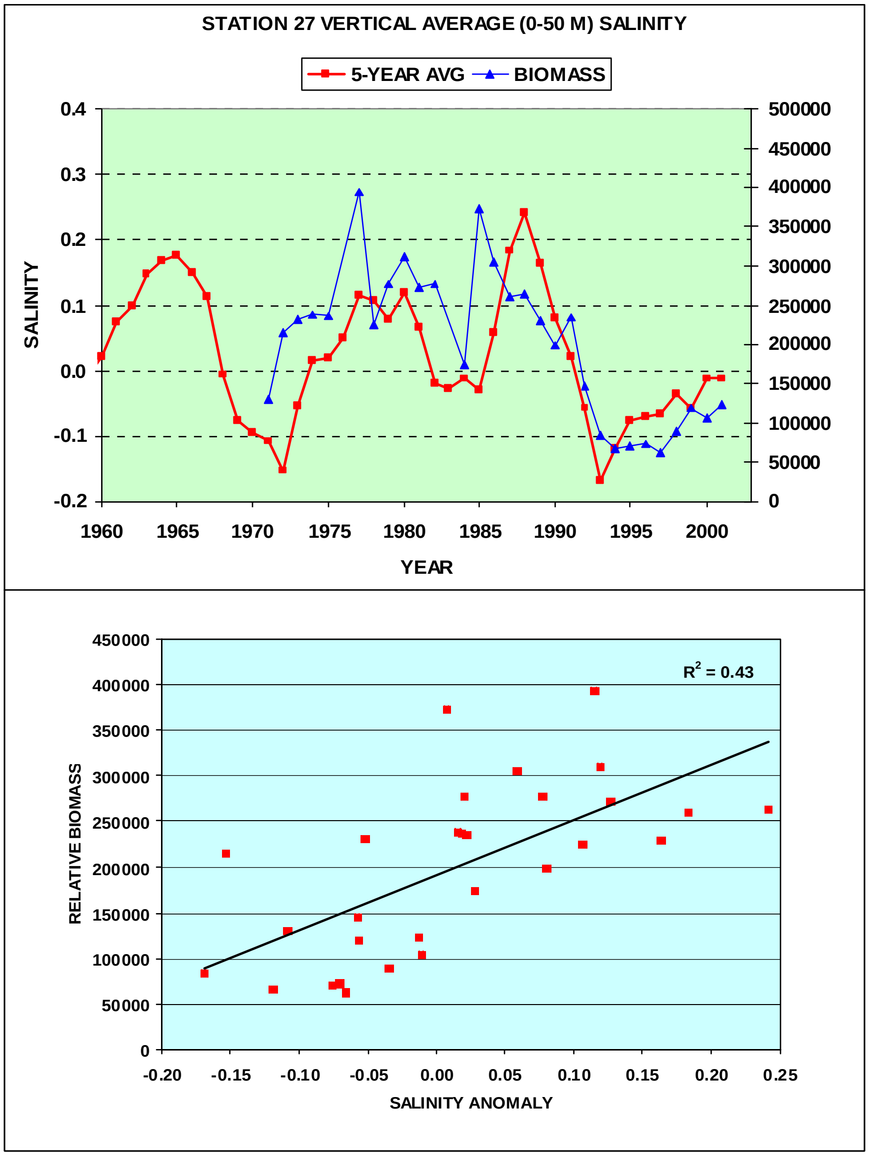


Fig. 11. Spring survey relative biomass index for thorny skate converted to campelen equivalents in NAFO Div. 3LNO and Subdiv. 3Ps for 1971-2002 and the Station 27 upper layer annual salinity anomaly. Data for 1976 and 1983 are not included in this plot.

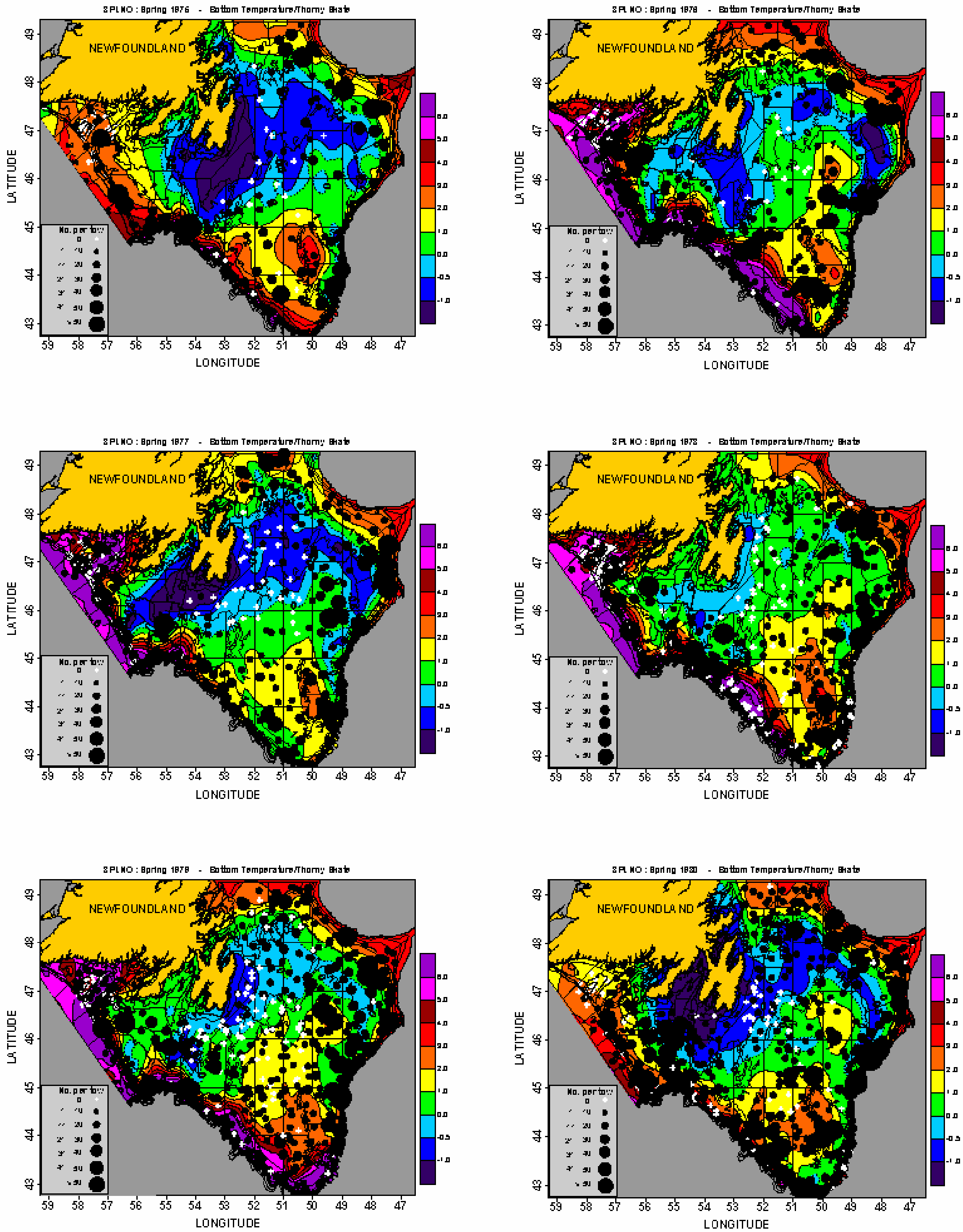


Fig.12a. Bottom temperature contour maps (in °C) for 1975-1980 based on data collected during the multi-species surveys of Div. 3PLNO. The numbers of thorny skate in each fishing set are shown as solid expanding circles. The white crosses represent zero catches.

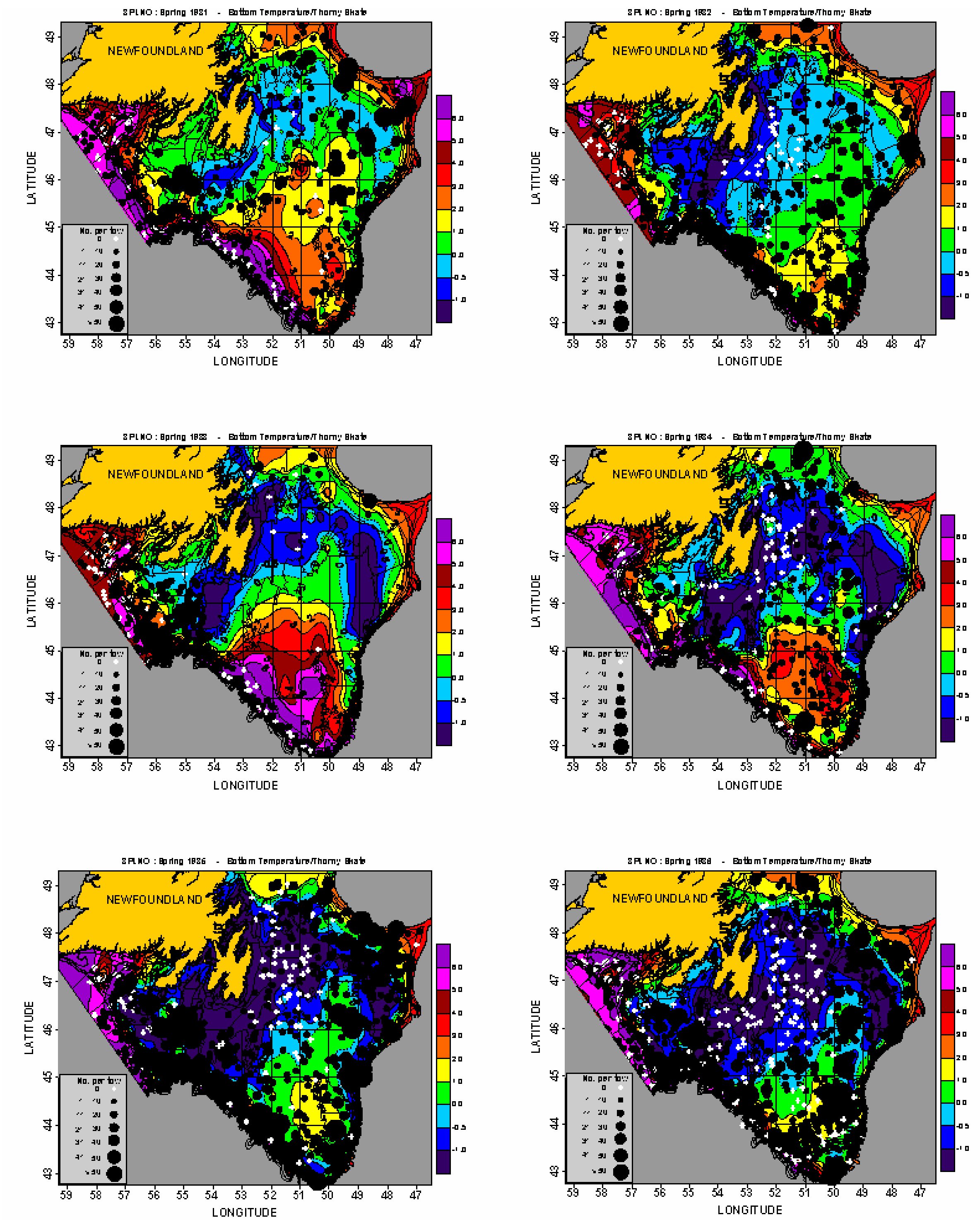


Fig. 12b. Bottom temperature contour maps (in °C) for 1981-1986 based on data collected during the multi-species surveys of Div. 3PLNO. The numbers of thorny skate in each fishing set are shown as solid expanding circles. The white crosses represent zero catches.

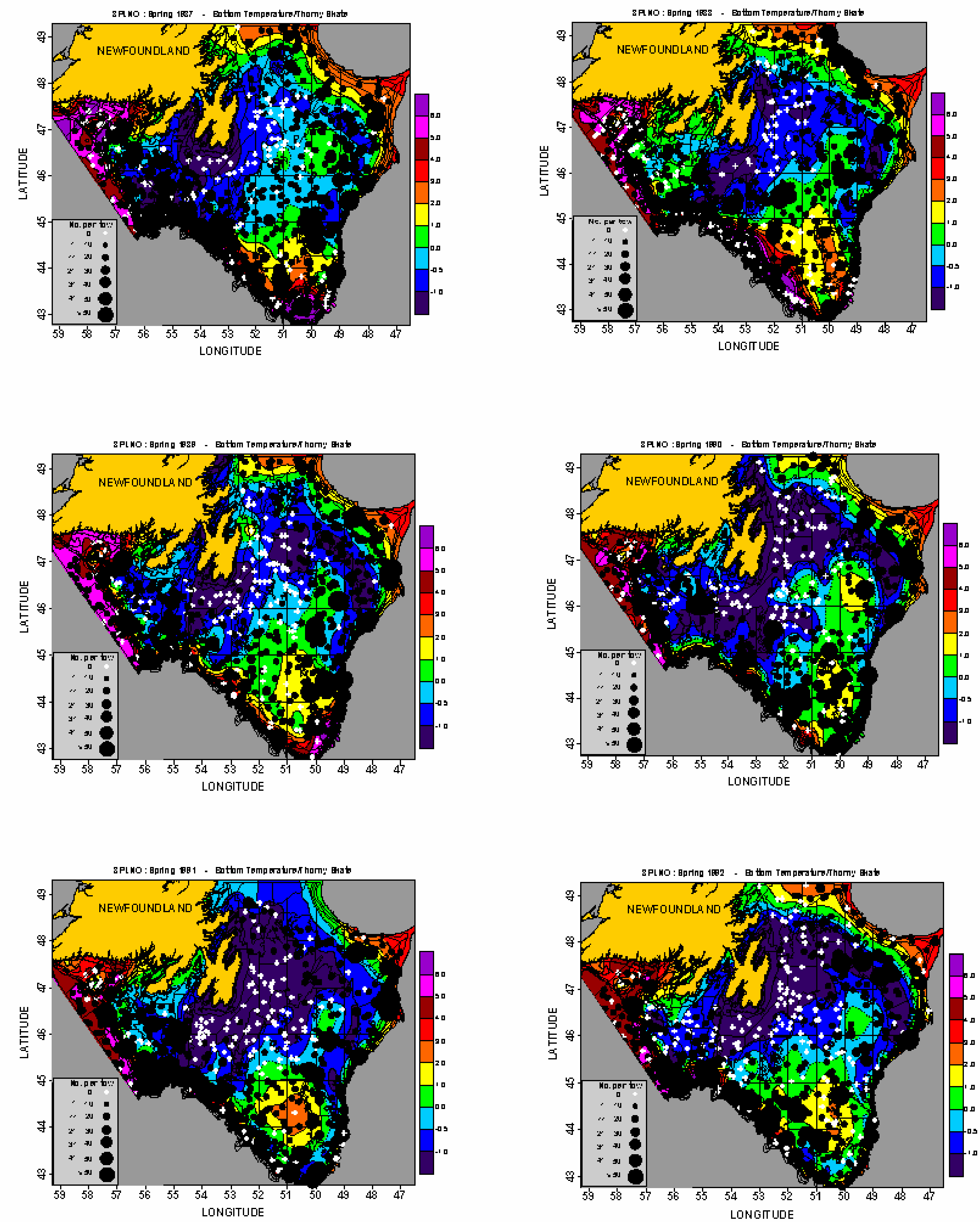


Fig. 12c. Bottom temperature contour maps (in °C) for 1987-1992 based on data collected during the multi-species surveys of Div. 3PLNO. The numbers of thorny skate in each fishing set are shown as solid expanding circles. The white crosses represent zero catches.

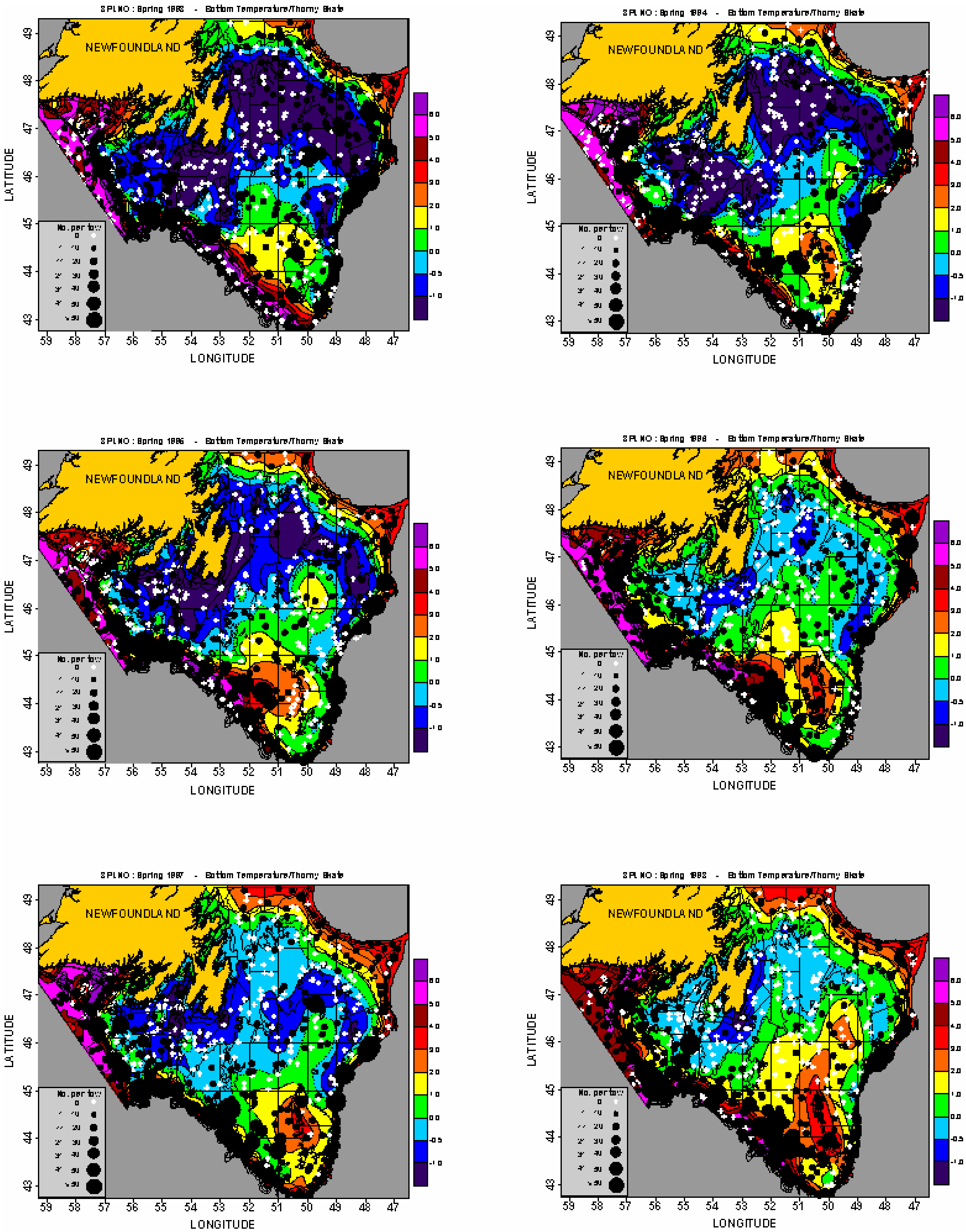


Fig. 12d. Bottom temperature contour maps (in °C) for 1993-1999 based on data collected during the multi-species surveys of Div. 3PLNO. The numbers of thorny skate in each fishing set are shown as solid expanding circles. The white crosses represent zero catches.

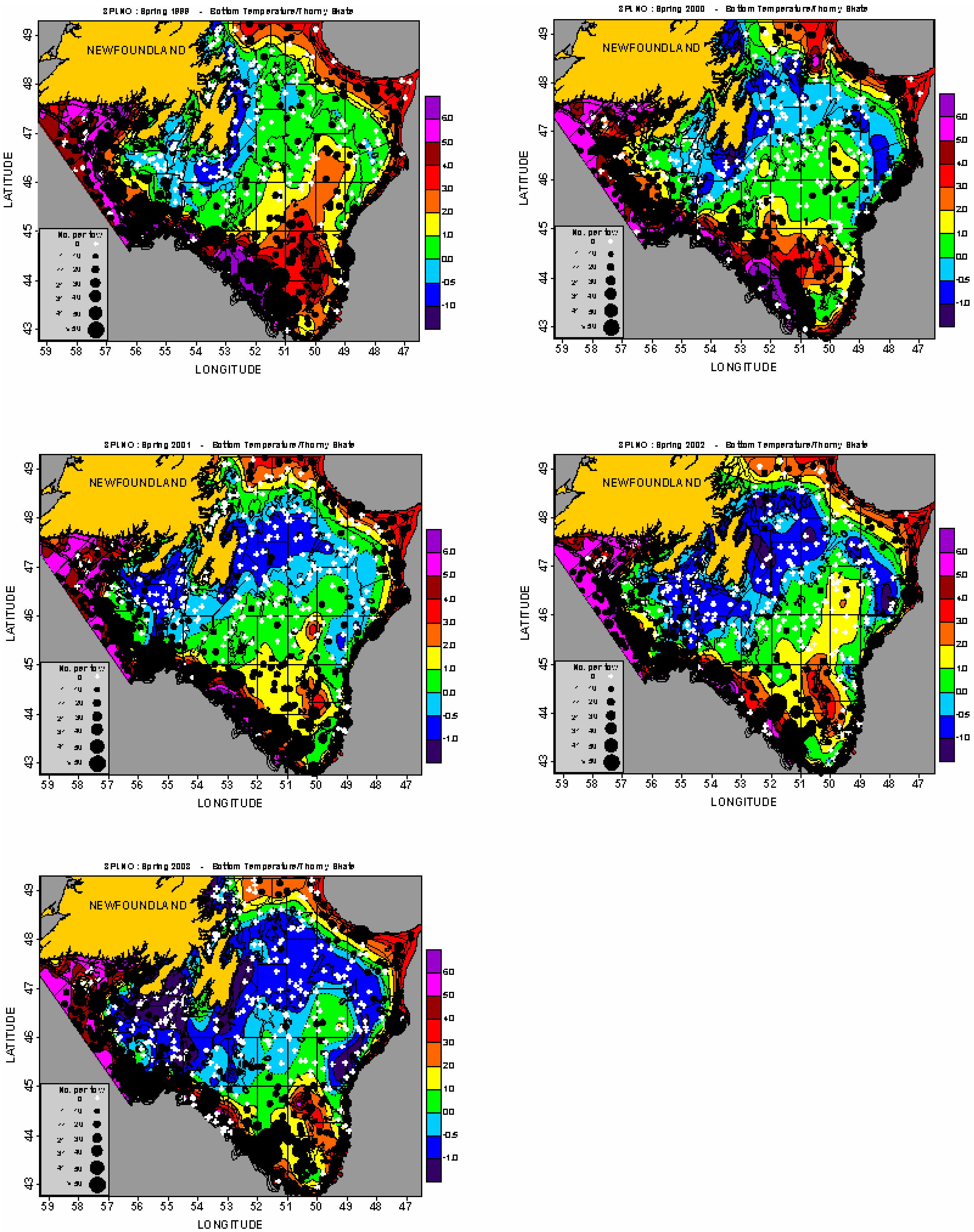


Fig. 12e. Bottom temperature contour maps (in °C) for 1999-2003 based on data collected during the multi-species surveys of Div. 3PLNO. The numbers of thorny skate in each fishing set are shown as solid expanding circles. The white crosses represent zero catches.