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Flemish Cap – A Review on Research Activities With Focus on Oceanographic Conditions

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Abstract

During the NAFO Scientific Council Meeting in September 1994, it was agreed that an overview paper on Flemish Cap Oceanography would be valuable information. As a first step, the author undertook a literature research on the ASFA database, and a historic overview of this research (Abstracts) was presented. In the continuation of this work a literature search based on the ICNAF/NAFO research documents was completed.

In this paper, a structured overview on Flemish Cap research activities in the recent past is presented with emphasis on the oceanographic aspects. The paper presents the kind of observations and the contribution by individual countries, the Flemish Cap topography, circulation and water masses, under seasonal and year-to-year criteria, and the work done on interaction issues between the environment and biota.

A bibliography is presented at the end of the paper.

Key words: Environment, Flemish Cap, oceanography, research

Introduction

During the NAFO Scientific Council Meeting in September 1994, the Standing Committee on Publications (STACPUB) discussed the potential submission of an overview paper on Flemish Cap Oceanography. The incoming Chairman of the Standing Committee on Fisheries and Environment (STACFEN) (M. Stein, EU–Germany) undertook the task to present an overview paper, provided the database permitted such an overview. As a first step, a literature research was done on the ASFA database, and a historic overview on summarized results of this research (Abstracts) was presented to STACPUB in June 1995. Continuation of this work was proposed with a literature search based on the ICNAF/NAFO research documents.

In reviewing the large amount of information contained in these documents, the author felt that it would be useful to prepare a structured overview on Flemish Cap research activities in the recent past with emphasis on the oceanographic aspects. Thus, the present paper in the first chapter deals with Material and Methods, which gives information on the kind of observations and the contribution by individual countries. In a further chapter the large scale background is given, comprising the Flemish Cap topography, circulation and water masses. The variability aspect is considered under seasonal and year-to-year criteria. The fourth chapter provides the reader with the work done on interaction issues between the environment and biota. In the fifth chapter the international cooperation in research is addressed. At the end of the overview, in the chapter on concluding remarks, the author shares his views on the evolution of the scientific approach to the Flemish Cap issues. This is followed by a section on the results reported in studies collated from the literature search in the ASFA database.

A bibliography is presented at the end of the paper consisting of Part A, which is based on the literature search in the ICNAF/NAFO archives, and Part B, which comprises literature found in the ASFA database.

Materials and Methods

For the literature research on the ICNAF/NAFO database, the available Indexes and Lists of Titles and Meeting Documents were reviewed (ICNAF, 1978, 1979a, 1979b; NAFO, 1985, 1990, MS 1991, MS 1992, MS 1993, MS 1994, MS 1995). In the subject index, Flemish Cap, Flemish Pass and Grand Bank were scanned. A total of 49 papers were retrieved from the ICNAF/NAFO archives. Twenty-nine of these research documents were of Russian/former USSR origin, 16 Canadian papers were considered, 2 from the United States of America, 1 from UK and 1 from Spain. To illustrate basic features of oceanographic components in the Flemish Cap area, figures were extracted from individual papers (as indicated in the figure captions). Since not all of the ICNAF/NAFO papers have abstracts, parts of the texts form the body and conclusions of the papers were taken to give a reasonable overview on the progress of research on Flemish Cap. The resulting abstracts are composed under the individual chapters, and the citations are given in Part A of the references.

To cover other sources of Flemish Cap literature, a search on the ASFA database was done on the most recent version of the database (May 1995). For key words, Flemish Cap, temperature and environment were taken and a total of 26 papers were retrieved from the database. The resulting abstracts are composed under the individual chapters, and the citations are given in Part B of the references.

Results

Large scale background

Topography

The Flemish Cap is a Bank situated in NAFO Div. 3M (Fig. 1), roughly 200 km in radius with the shallow parts being situated at 47°N, 45°W. Depths range between 125 m and 700 m (Fig. 2). At the southern rim of the bank there is a steep slope. To the west, water depth gradually increases to about 350 m, before the Flemish Pass is reached. Flemish Cap is an isolated bank, with the 1 100 m deep Flemish Pass separating it from the Grand Bank (Akenhead, MS 1982).

Circulation of water masses

The general circulation of water masses is outlined in Fig. 3. From the northwest, the cold Labrador Current transports arctic water to the region off Newfoundland, the Grand Bank, and Flemish Cap. At the edge of the Grand Bank of Newfoundland, the Cold Core of the Labrador Current (less than 2°C and less than 34.3 PSU) meets and mixes with the warm, saline waters of the North Atlantic Current (temperatures above 12°C, and salinities above 35.5 PSU). Due to the boundary formed on the west of this region by the Grand Bank and the permanence of the two current systems, the area is quite well understood on the average dynamic topography (Robe, MS 1974). The average dynamic topography for April, based on 32 years of dynamic height data (Fig. 4), shows the mean characteristics of the circulation to the east of the Grand Bank: The Labrador Current follows the slope of the Grand Bank closely with a typical speed of 30 cm/sec. The North Atlantic Current maneuvers its way 50–150 miles off the Bank with a permanent meander near the Newfoundland Rise and has current speeds of 30–50 cm/sec. Between these two current systems there is a region of mixed water forming a dynamic low or trough.

Geostrophic circulation

Observations made during 1973 by the International Ice Patrol (Robe, MS 1974), revealed a current regime (Fig. 5) in which the North Atlantic Current was about 40 miles further north than usual and was running against the Tail of the Bank. This in turn forced the Labrador Current up to the banks proper. The dynamic topography presented in Fig. 5 indicated that the excess Labrador Current flow was incorporated in a large pool of cold (less than 5°C), slowly moving water centered on 42°50'N, 48°20'W. In the center of this cold pool was a strong, anticyclonic eddy with a velocity of 28 cm/sec. This situation was confirmed by the presence, during this period, of large numbers of icebergs around 43°N which did not appear to be moving further southward. At the northern end of this dynamical flat region, at 45°40'N, is an area where a large portion of the Labrador Current branches from the main flow and moves eastward south of Flemish Cap.

Kudlo and Borovkov (MS 1975a) in an analysis of the geostrophic circulation in Newfoundland waters, reported changes of circulation on the eastern slopes of the Newfoundland Grand Bank and Flemish Cap Bank where circulation acquired a regular typical pattern. As can be seen from Fig. 6 there was slow anticyclonic motion on the Grand Banks, a swift, narrow current band over the Flemish Pass, and typical, anticyclonic motion on Flemish Cap Bank.

Hill *et al*. (MS 1973) worked on hydrographic sections crossing the Labrador Current between Flemish Cap and the Grand Bank. Geostrophic velocities on the Flemish Cap-Grand Bank section, relative to a 600 m reference level, were computed. The reference level of 600 m was chosen by fitting the geostrophic velocity profile between stations 47 and 48 (Fig. 7) to the residual currents perpendicular to the section recorded at Station B during the 12 hr 25 min tidal cycle nearest to the time of occupation of the series stations. It was seen that the Labrador Current had a maximal velocity of about 55 cm/sec, extended in depth to at least the adopted reference level and appeared to be a shelf edge phenomenon, in that it lies against the edge of the Grand Bank itself. The normal clockwise gyre around the Flemish Cap as reported by Kudlo and Burmakin (1972) was seen to be reversed at the time of sampling, but it was weak having a maximum measured mean southerly component velocity of 8.4 cm/sec near the surface.

Drifting buoys

As part of the *NAFO Flemish Cap Experiment* a set of six satellite-tracked drifting buoys were released

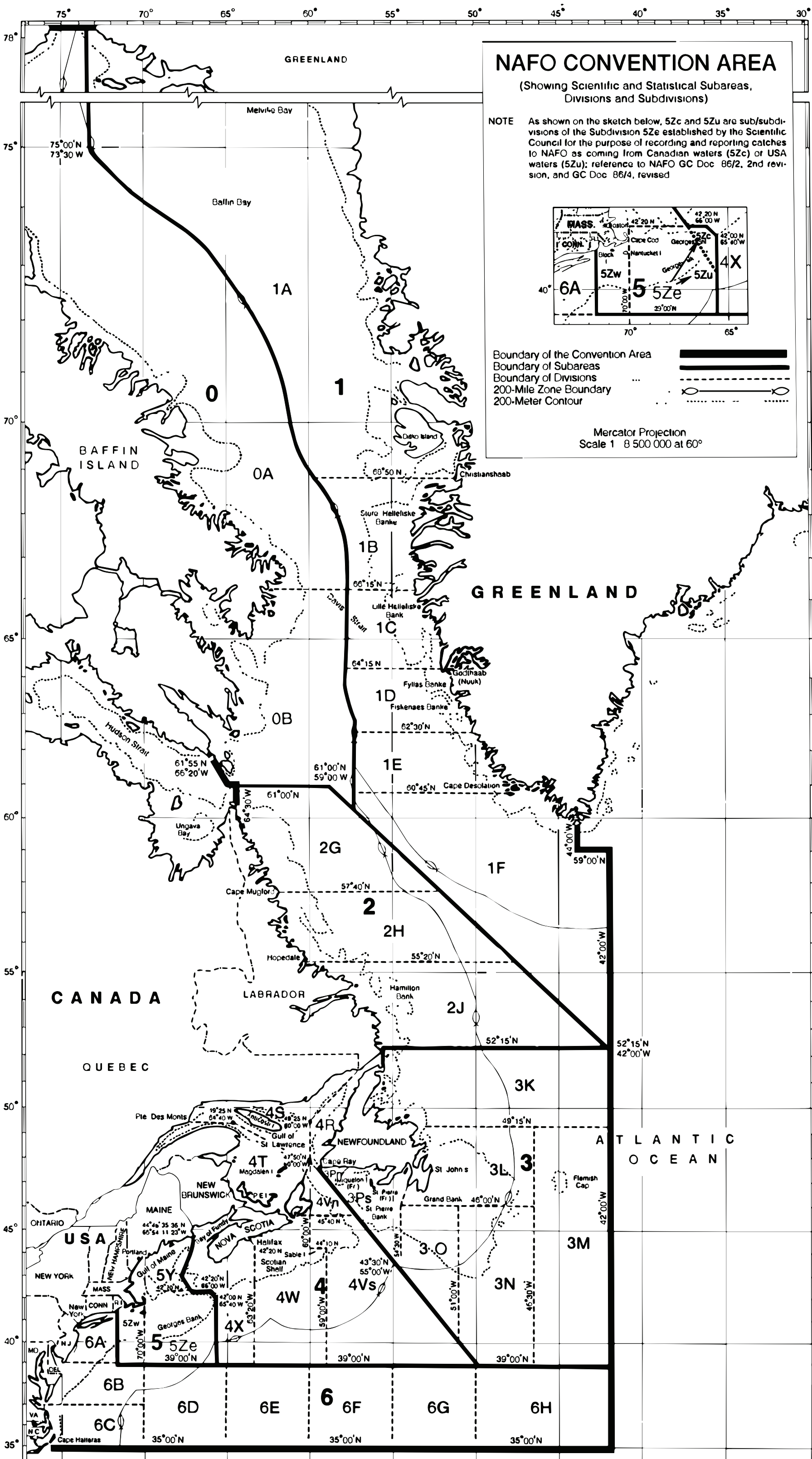

Fig. 1. Location of Flemish Cap (Div. 3M) in the NAFO Convention Area.

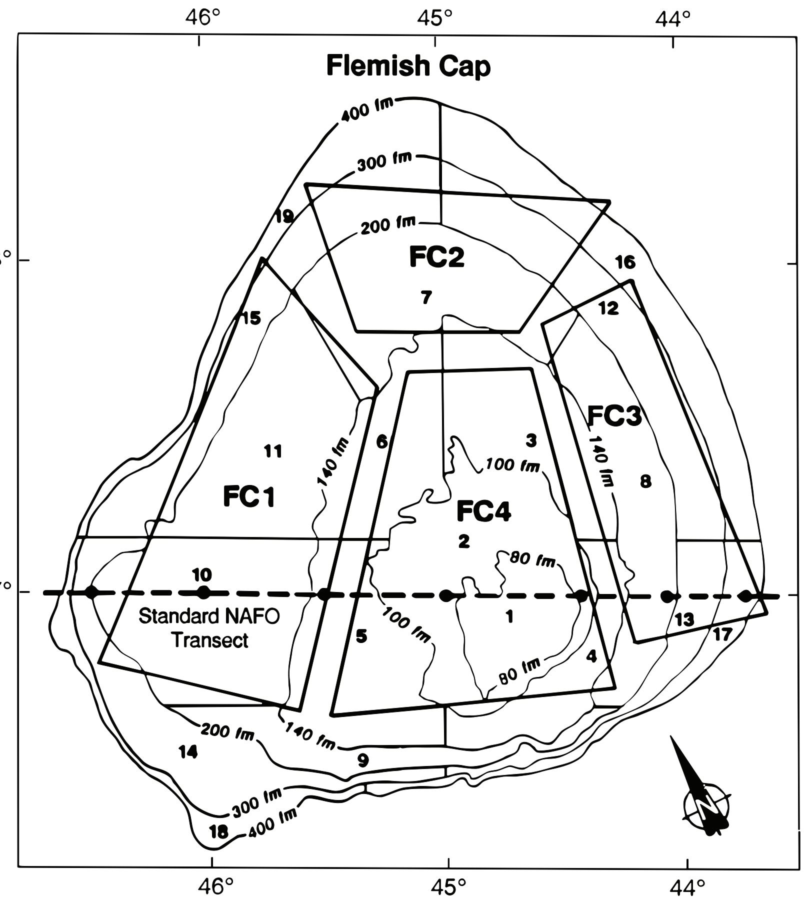

Fig. 2. Flemish Cap area showing the standard NAFO transect and the areas where temperature and salinity anomalies were examined (from Colbourne, MS 1993).

on Flemish Cap between January, 1979, and May, 1980. The position of each buoy was monitored by Service Argos in Toulouse, France (Ross, 1981). Most buoys experienced a very slow motion while on the Cap with a general trend toward an anticyclonic rotation. However, the path of each buoy was unique (Fig. 8a, b). Buoy 2 422 managed to get to the northwest slope of the Cap and then proceeded in a very regular track around the outer limits of the Cap. This could quite possibly show the outer branch of the Labrador Current.

Currents

Based upon current meter records at the western rim of the Flemish Cap, Hill *et al.* (MS 1973) revealed a relatively steady north-westerly drift of about 3.5 cm/sec. There was considerable variability in both velocity and direction about the mean flow at each of the three points on the Flemish Cap section. This suggests that the gross variability found in the residual drift regime was the result either of large-scale changes in the advective drift of waters to the west of the core of the Labrador Current, or of a change in the position of the core itself. Finally, the temperature and current meter data suggest that a third distinct residual drift regime occurs at the eastern end of the Flemish Cap section. Normally, there is a clockwise gyre round the Flemish Cap itself, and the essentially north-west going drift (mean daily velocity 3.5 cm/sec) found in both records at this station on and after 21 April, support this view. The atypical south-going component of drift found in both records on 20 April is presumably a consequence of the north-westerly gale that blew for most of the day and reached 40 knots at times in the vicinity of the meter station.

Four moored current meter strings were deployed during the *NAFO Flemish Cap Experiment* for a period of six months in 1979. The only surviving data records are a complete suite of current velocity, temperature and salinity at 54 m and 184 m depth, and a partial record of current velocity with complete records of temperature and salinity at

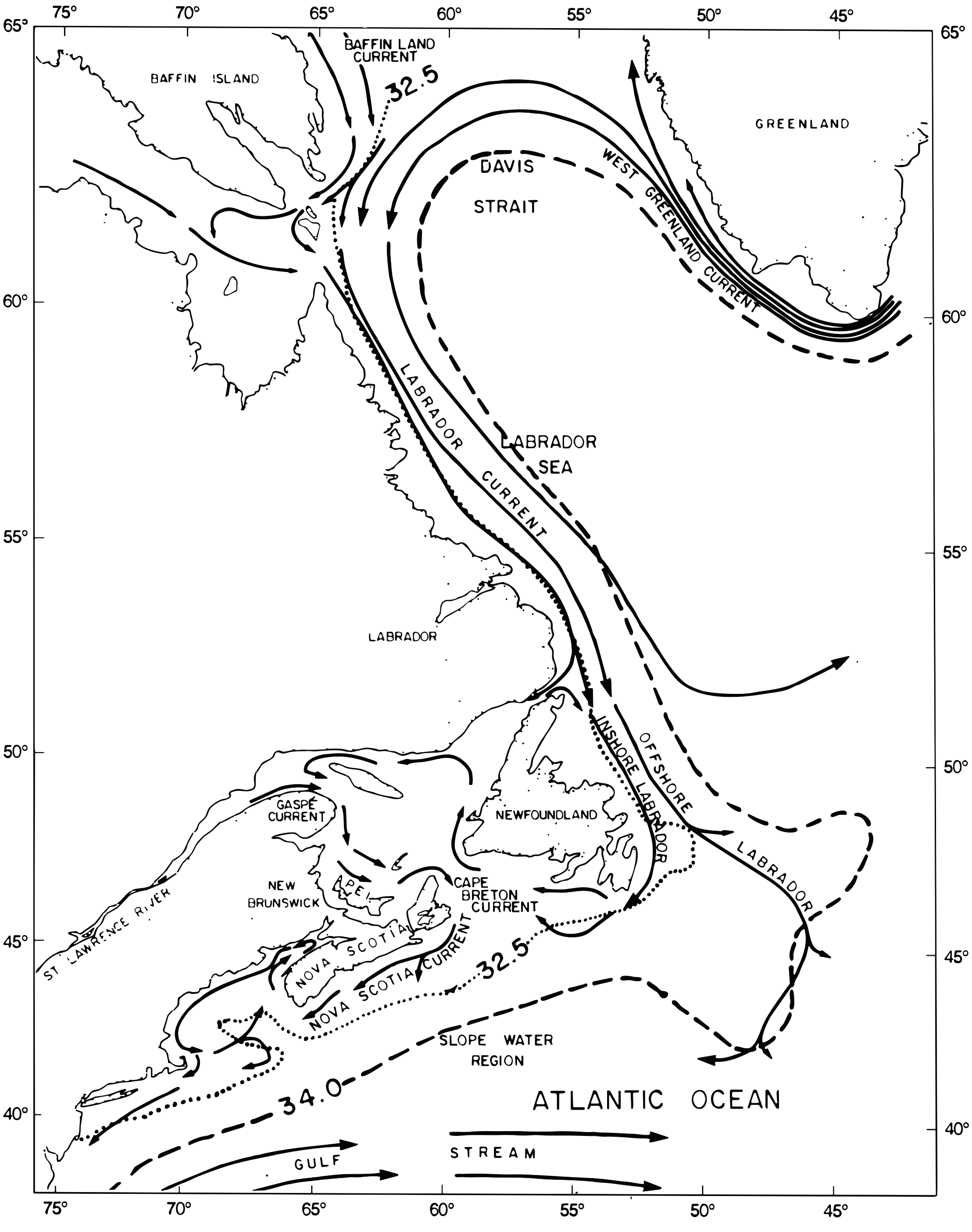

Fig. 3. Northwestern Atlantic Coast showing general surface circulation pattern. Approximate locations of the 32.5 PSU and 34.0 PSU salinity isopleths at 30 m depth are also shown (from Trites, 1982).

185 m from another mooring string (Ross, MS 1980). The mean currents in all cases were very closely tied to the direction of the local bathymetry. The records reinforce the idea that the residual circulation is anticyclonic but very weak. The original time series were dominated by the semi-diurnal tidal signal. Apart from the very weak amplitude of the variations in current speed, the most notable feature is the existence of a very periodic signal of about 4 days – particularly in the energetic period during the spring. The signal becomes much more quiescent during the summer, most likely a result of a

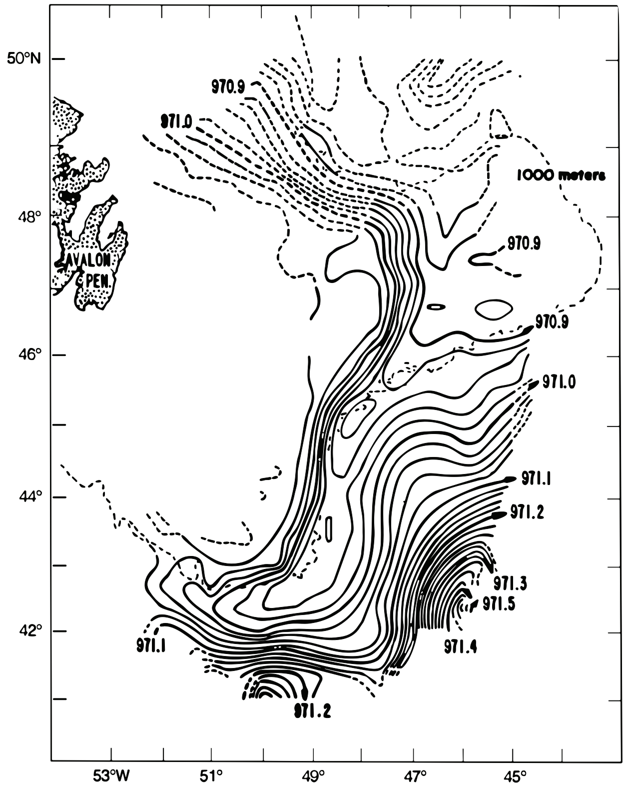

Fig. 4. Average dynamic topography for April computed from 32 years of data (from Robe, MS 1974).

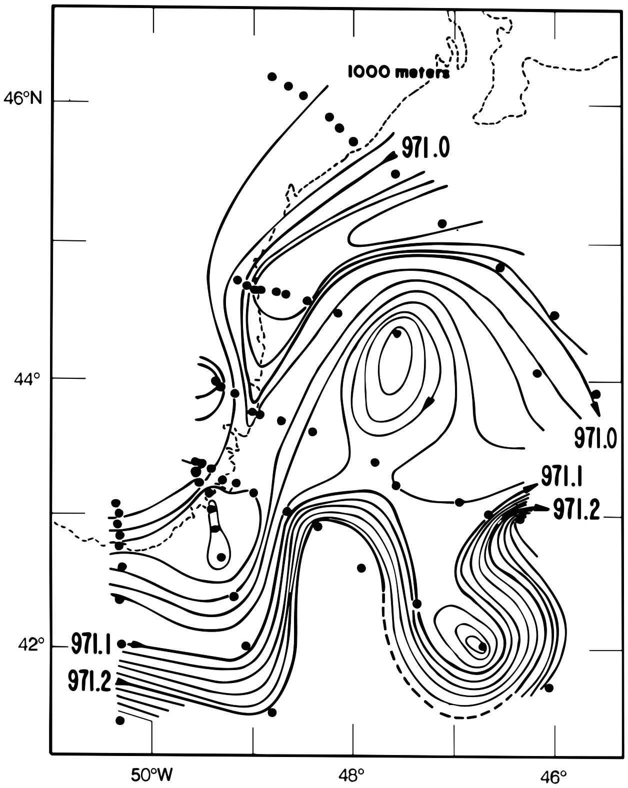

Fig. 5. Dynamic topography for May 1973, relative to 1000 decibars (from Robe, MS 1974).

decrease in wind forcing. One would be inclined to try to fit some sort of topographically trapped wave to the Cap that would give a resonant mode around the Cap. This might also be the source of the anticyclonic residual current. This has not yet been investigated and has to remain speculative (Ross, MS 1980).

Along the Flemish Cap transect Colbourne (MS 1993) mapped the currents with a hull-mounted 300khz RDI Acoustic Doppler Current Profiler (ADCP) at a spatial resolution of 4.0 m vertically by approximately 1.5 km horizontally. Fig. 9 shows the vertical distribution of currents over the Flemish Cap during early July 1993, the negative values correspond to southward flowing water. Preliminary analysis of this data showed the offshore branch of the Labrador Current in the Flemish Pass area up to 200 m deep with current velocities of about 15 cm/sec in a general southerly along-shelf direction, further onshore near the center of the offshore branch, current velocities reached 40–50 cm/sec. Over the Flemish Cap between 500 and 700 km offshore, the circulation was predominantly anticyclonic with northward currents ranging from 5 to 15 cm/sec over the shoreward portion of the Cap and southward currents over the offshore portion with speeds again ranging from 5 to 15 cm/sec. A gyre with a nominal width of about 200 km (dimension of Flemish Cap) and an average current speed of about 10 cm/sec corresponds to a rotational period along its periphery of approximately 10 weeks.

One of the main mechanisms for the breakdown of the anticyclonic circulation was the strength and frequency of wind forcing in the area resulting from the passage of major storm events. Kudlo *et al.* (1984) have shown that the frequency of meandering type flow across the bank is greatest during the winter months when the mean wind speed is the greatest. To determine the relative stability of the gyre over time, particularly in the spring and summer when the retention of fish larvae is most important, it will be necessary to analyse the climatic data in the area to determine if conditions were favourable for prolonged periods of anticyclonic circulation. As indicated above, most likely variations in the Labrador Current and the Gulf Stream also play important roles in the circulation of the area as well.

Water masses

Distribution of temperature and salinity along the Flemish Cap section was given by Karasyev (MS 1962). The July, 1961 conditions revealed cold arctic

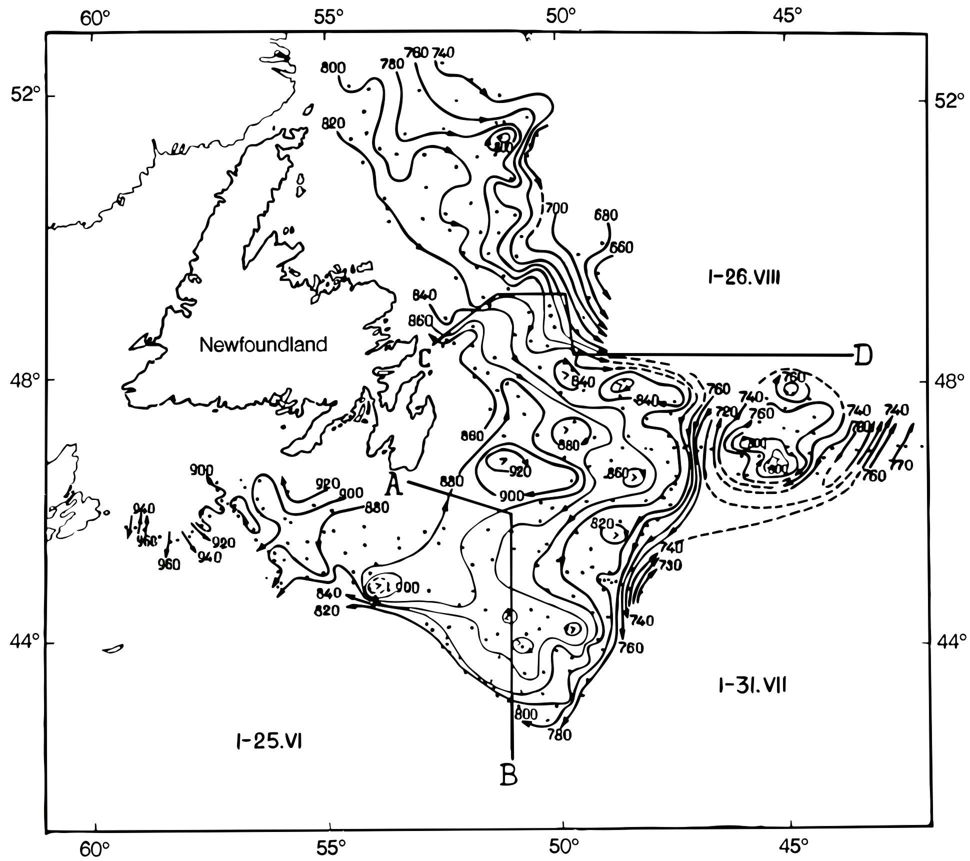

Fig. 6. Geostrophic circulation in the Newfoundland area in June–August 1973, 0/200 decibar, R/V *Perseus III* (from Kudlo and Borovkov, MS 1975a).

water on the Grand Bank (Fig. 10). The thermohaline front was situated at the eastern slope of the Grand Bank. Over Flemish Cap Bank water of less than 4°C was found. A distinct thermocline at about 50 m depth separated warm surface water of more than 10°C from the colder intermediate waters. Canadian observations performed during July, 1973 (Templeman, MS 1974) revealed similar thermohaline fields along the Flemish Cap section (Fig. 11). Below a seasonally heated surface layer, the cold water of Labrador Current origin emerged from about 50 m down to the bottom of the Grand Bank. The subsurface thermohaline front is "masked", i.e. the thermohaline gradients were only visible at depth. On Flemish Cap Bank bottom water temperatures ranged from 3°C to 4°C. Highest salinity was encountered in the deep layers of the Flemish Pass (named Flemish Channel in Templeman's figure), and east of Flemish Cap below 100 m depth.

Recently, a publication on thermohaline properties on Flemish Cap was presented by Colbourne (MS 1993) during the NAFO Scientific Council Meeting 1993 (Fig. 12, 13). Based on all available historical data from the early-1930s to 1992, the June/July temperature for this time period in the upper water column ranged from 4°C at 50 m depth to about 9°C to 10°C near the surface. In deeper water (50 m to the bottom) the temperature ranged from 2.0°C to 3.5°C in the Flemish Pass area, in the offshore branch of the Labrador Current, and from 3°C to 5°C offshore of the Cap where the influence of the Gulf Stream was evident. The corresponding average salinities generally ranged from 33.5 PSU near the surface to 34.75 PSU near the bottom over the Flemish Cap in about 300 m depth. In water depths greater than 300 m salinities were generally greater than 34.75 PSU. Dissolved oxygen levels of 7.0–8.0 ml in the upper 100 m of the water column over the Flemish Pass area and values ranging from 6.0 to 6.5 in water depths of 150 m to the bottom over the bank were observed in early July, 1993 (Fig. 13). The corresponding oxygen saturations ranged from 100% from the surface to about 40 m depth and to 80% in the deeper water over the bank indicating a well oxygenated water column. Keeley (MS 1982) using techniques of empirical orthogonal

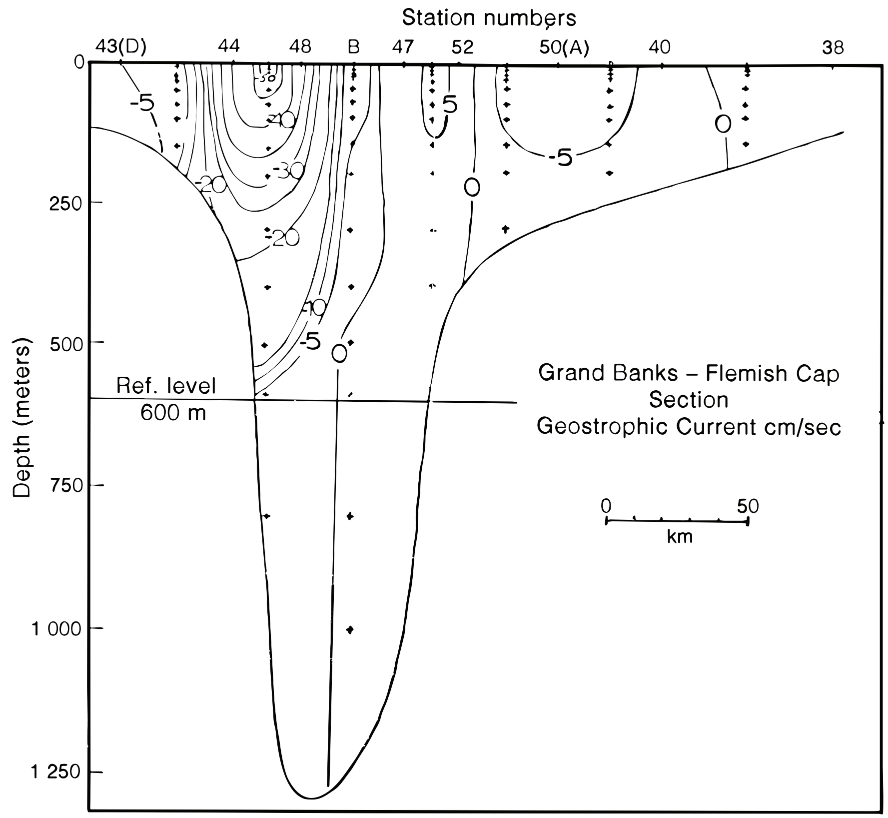

Fig. 7. Geostrophic currents, Grand Bank–Flemish Cap section (from Hill *et al.*, MS 1973).

function and cluster analyses, showed that it is possible to discern regional differences in water types in the region of the Flemish Cap. The data from the months of April and May suggested six different regions of the Cap, with about an 85% probability that these regions are different statistically. In particular, one of these regions, directly west of the Cap and east of the Flemish Pass, would appear to be a region of mixed water types (Fig. 14).

Variability aspects

Seasonal

First results on seasonal variability were found in Burmakin (MS 1971). He tried to obtain a mean curve of the yearly variation of water temperature in the 0–200 m layer for particular regions of NAFO sections. One example is given in Fig. 15 for the Flemish Cap section, west off the Cap. Lowest temperatures were encountered during April/May, maximum temperatures were reached during October. Based on ships-of-opportunity data, Bailey (MS 1982) provided annual cycles of sea-surface temperature on the Flemish Cap for the years 1962–81. His results differ consistently from Burmakin's (MS 1971) as concerns the month's of minimum and maximum temperature (Fig. 16). Whether this difference is due to the different time periods in both papers cannot be answered here. Colbourne (MS 1993) analyzed historic data sets from the Flemish Cap which encompassed the period from the early-1930s–92 (see above, and area FC1 in Fig. 2). As can be seen from his data (Fig. 17), highest thermal amplitudes of the seasonal cycle were observed in the near surface layer (0 m and 20 m). Lowest temperatures of about 3°C were found during February/March, and highest temperatures of about 14°C at the end of August. The seasonal signal diminishes rapidly with depth. At 50 m depth which is the lower end of the thermocline, it was hardly to be discovered. From 100 m down to the bottom mean conditions were nearly homothermal. Seasonal variation of surface salinities (Fig. 18) may be described by a flat harmonic oscillation which was only detectable at 0 m and 20 m depth. Similar to temperature, the deep layers revealed homogenous conditions throughout the year.

Year-to-year

Comparing the 1973 observations on Flemish Cap with the long-term database, Templeman (MS 1974) concluded that there was colder water and more water below 2°C above Flemish Cap than in

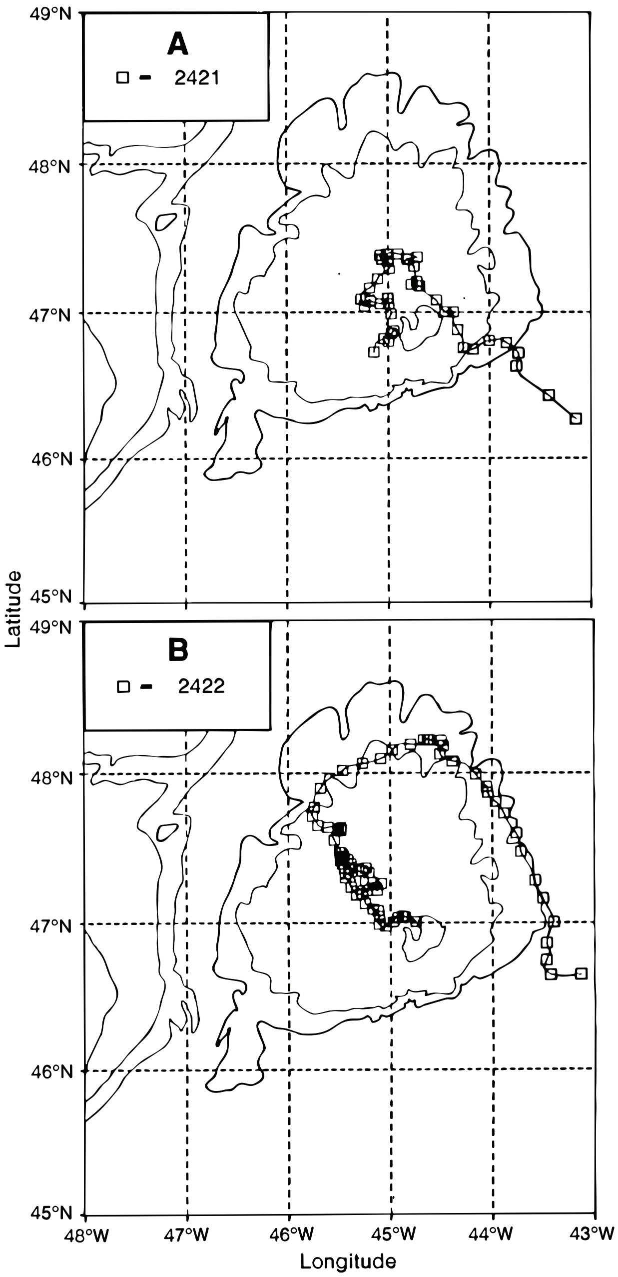

Fig. 8. Drift track of buoys (**A**) 2421, first point at 46.72°N, 45.16°W at 1800z day 14, last point at 1800z day 54, symbol every 24 hours; (**B**) 2422, first point at 46.99°N, 44.50°W at 1800y day 77, last point at 0600y day 148, symbol every 24 hours (from Ross, 1981).

any year of the 1951–73 period except 1972. Oceanographic station data from 1934 to 1976 were used to obtain weighted mean temperature of the 0–200 m layer in the Flemish Cap region (Hayes *et al*., MS 1977). To investigate the variation of water properties on Flemish Cap, Hayes *et al*. (MS 1977) considered a fairly small area on the southwest side (46°40'N–47°00'N, 45°00'W–46°00'W). On a temperature-salinity diagram, the results appear in two groups. The first group tended to be co-linear with a negative slope (warmer, low salt content to colder, high salt content). The points were generally in the mixed water region, but approach Labrador Current characteristics in the colder years. The variation in water properties did not appear to result from a varying mixing ratio of Labrador and North Atlantic Current waters which would yield a line with positive slope approximately along a constant density line. Instead, significant variation existed not only in water temperature but also in density. The changes in density were generally observed throughout the water column and not in an isolated layer. The second group of points are from 1971–74 and 1976, and are almost purely Labrador Current water. The large variation in water density suggested the occurrence of some form of upwelling in the Flemish Cap region. For example, the water observed at the 200 m depth in 1957 and 1959 was characteristic of Labrador Current water from the 300–400 m depth. However, Flemish Cap is too deep to yield the type of wind-driven upwelling normally observed along a coast or a shelf break. Upwelling could result from a divergence of the wind-driven Ekman transport. The vertical velocity driven by the divergence of the Ekman transport has been averaged for the months April to June for 1951 to 1976 at 45°N, 45°W. The results do not resemble closely the variations of water temperature or density, although a weak relation may exist by which lower density water is found during periods of lower upwelling velocities. The tendency toward Labrador Current properties on Flemish Cap in recent years could have resulted from a transport of water from the current toward Flemish Cap. However, the southeast Ekman transport at 45°N, 45°W, averaged for the months April to June, exhibits no significant recent increase. The presence of Labrador Current water on Flemish Cap could be related to the northward movement of L0 (latitude of the zero transport contour along the 45°W meridian) during recent years, causing a larger portion of the Labrador Current to flow eastward along the north side of Flemish Cap instead of heading south along the eastern edge of the Grand Bank.

As a presentation at the *NAFO Symposium on Environmental Conditions, 1970–79*, Keeley (1982) dealt with departures from the mean of potential temperature and salinity along the Flemish Cap Section in the decade of the 1970s. The analysis suggested that the early part of the decade showed colder, fresher water than the mean dominating the water column. In the latter part of the decade warmer, saltier water prevailed. The change over from cold, fresh to warm, salty conditions seems to have occurred sometimes in 1976 or 1977. Anomalous intrusions of subzero water masses into the

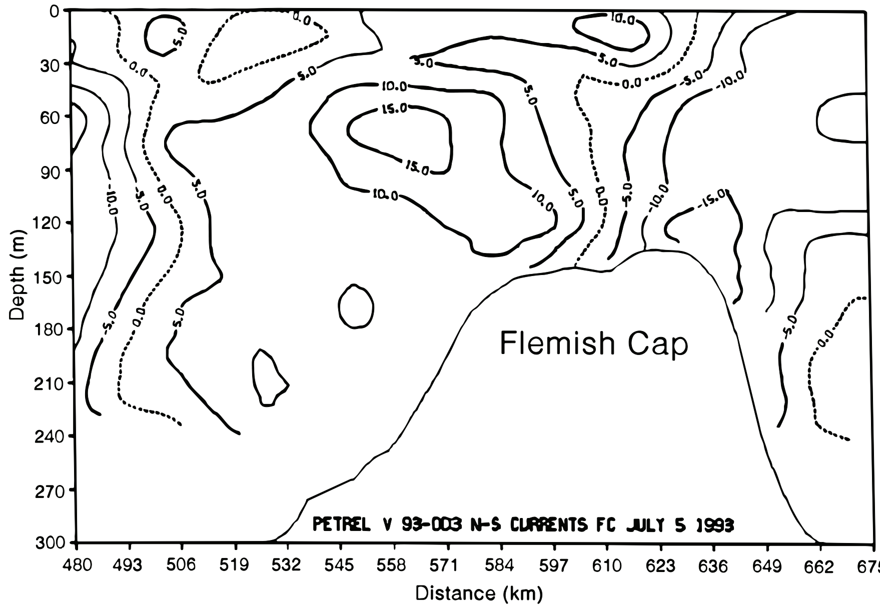

Fig. 9. Vertical distribution of the North-south current field over the Flemish Cap. Negative currents are southward, from ADCP survey (from Colbourne, MS 1993).

northern and eastern slopes of Flemish Cap Bank were observed during April–July 1984 (Borovkov and Burmakin, MS 1985). These intrusions were registered for the first time since 1960, and were attributed to advection from the Labrador Current.

Interaction environment-biota

Projects

The majority of research projects in the Flemish Cap area had a fishery related background with hydrographic measurements at the fishing positions and at standard oceanographic stations. The acquired data were usually treated to extract environmental influences on the biota. Akenhead (MS 1982) revealed positive effects of northerly winds on cod year-class strength. He speculated that northerly winds drive and strengthen the Flemish Cap gyre. The USSR trawl survey data provided evidence of the correlation between the area occupied by cold waters in NAFO Div. 3L and the number of juvenile cod on Flemish Cap (Borovkov *et al.*, MS 1989). If the area occupied by bottom waters with temperatures much below the norm increases in Div. 3L, the number of cod (mean catch-per-hour tow) of respective year-classes at age 1, 2, 3 on the Flemish Cap increases too ($r = 0.902$, $r = 0.846$, $r = 0.908$). Interaction between the mode of circulation on Flemish Cap and the distribution of cod eggs was addressed by de Cardenas and Gil (MS 1994). Based on Kudlo *et al.* (1984) it was shown that during a circulation pattern with a west-east component, transportation of eggs from the Flemish Pass region to the Cap is favoured. The strong recruitment of 1986 could have been due to entrainment of large masses of eggs located in Flemish Pass during the second half of April 1986. With a simple multiple linear regression analysis, Hayes *et al.* (MS 1977) suggested that the significant factors influencing cod recruitment on Flemish Cap are the total cod population of Flemish Cap, meridional and zonal Ekman transport, and the mean April sea temperature. In a series of ICNAF and NAFO contributions Konstantinov (MS 1975, MS 1980, MS 1981) correlated water temperature and strength of cod year-classes on the Flemish Cap. Fig. 19 shows a result of his computations. Rice and Evans (MS 1986) used recruitment predicted from the gross recruitment method, rather than the recruitment-per-unit stock method, and the actual temperature and salinity April–August measures, rather than the principal component scores of the environmental analysis. All analyses produced similar results: deviations and recruitment size covaried, as did stock and the environmental measures. It was warmer in the early-1960s when the stock was large, and colder in the late-1970s, when stocks were depressed. Neither influence had systematic effects on recruitment, however.

Evidence of hemispheric coherence

Burmakin (MS 1971) reported that fluctuations of water temperature in the areas of the Northwest Atlantic and in the Barents Sea occur in "anti-phase".

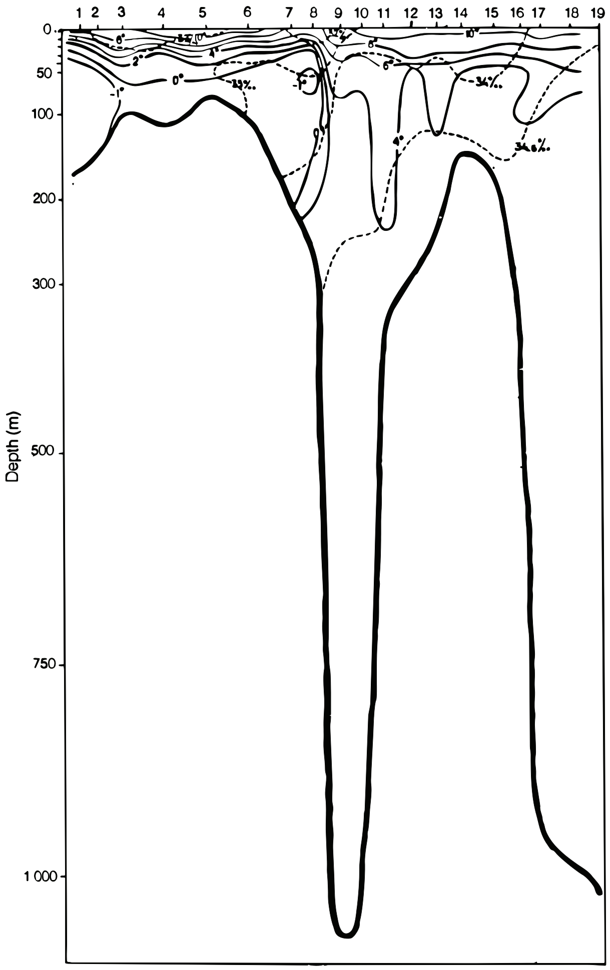

Fig. 10. Flemish Cap section: Distribution of temperature and salinity, July 1961 (from Karasyev, MS 1962).

This was observed between variations of temperature on Station 27 and temperature variations along the Kola-Meridian section. Konstantinov (MS 1975) concluded "that the fluctuations in the hydrological regime in the south of the Grand Bank and on the Flemish Cap Bank affect the abundance of commercial species not only in these areas but, after some time, in the north-European seas as well." A possible explanation for the anticipated west-east coherence could be found in the North Atlantic Oscillation (NAO) Index (Rogers, 1984). The NAO index is the difference in winter (December, January and February) sea level pressures between the Azores and Iceland and is a measure of the strength of winter westerly winds over the northern North Atlantic. Strong NW winds, cold air temperatures and heavy ice in the Labrador Sea are associated with a strong NAO index (Drinkwater, MS 1994).

International cooperation in research

NAFO Flemish Cap Experiment

Considering the influence which the mesoscale water circulation exerts on commercial fish reproductivity, the Polar Institute in Murmansk (PINRO) arranged in 1980, in the framework of international collaboration, a series of detailed oceanographic surveys in the Flemish Cap area (Borovkov and Kudlo, MS 1981). According to the results of these surveys (Fig. 20) during spring-summer period of 1980 the dominating form of water circulation over the bank were non-stationary meanders. Only in early May there occurred an anticyclonic vortex over the top of the Bank which was weakly developed during summer and was displacing towards the northwestern slopes. Such a long absence of an anticyclonic gyre over the Bank was for the first time observed during 3 years of detailed spring-summer surveys. Following the hypothesis that water circulation is one factor in generating strong year-classes of fish on Flemish Cap Bank, circulation instability, and significant changes of current directions in the absence of anticyclonic motion, results in losses of considerable ichthyoplankton communities from the bank.

Concluding remarks

During the review of available ICNAF/NAFO documents (see Bibliography PART A) it was possible to detect the evolution of the scientific approach to one of the more unique fishing grounds in the Northwest Atlantic, the Flemish Cap. Being only of marginal scientific interest during the early years of ICNAF research in the 1950s, there is no reference available on the oceanographic issue during the first decade of ICNAF. In the early-1960s, the USSR scientists published the first results. Another paper, again of USSR origin, appeared at the end of the 1960s. During the 1970s scientific interest on this area increased. The publications concentrated mostly on the descriptive aspect of the observed thermohaline properties. Seasonal approaches were the first to meet the variability problem. Year-to-year variation was first addressed by Templeman (MS 1974). The time-series approach of data collection evolved more during the following years. When a general understanding of Flemish Cap water mass circulation and their potential impact on recruitment of demersal fish was reached, the NAFO Flemish Cap Experiment was designed in the late-1970s, and the field observations were carried out until the early-1980s. A combined input of classical hydrographic measurements on the mesoscale, plus direct current measurements and drifting buoys, along with some useful satellite imagery (Fig. 21) during this experiment, formed the

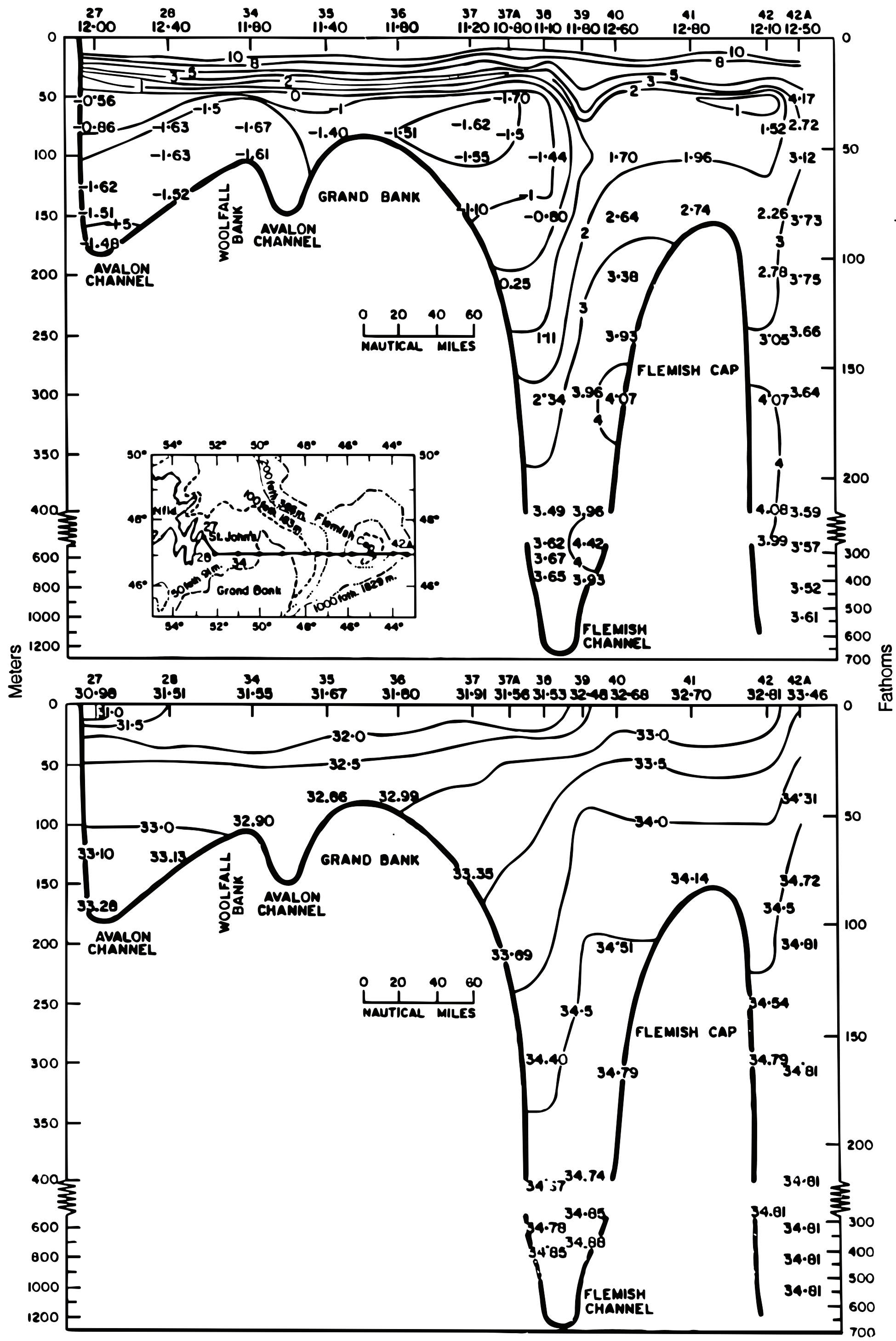

Fig. 11. Temperature (°C, above) and salinity (PSU, below) along the Flemish Cap section July 1973 (from Templeman, MS 1974).

existing picture which is now available. However, research activities did not stop after this international experiment. At a national level, research was carried on in the area, databases were analyzed and results were shared with the scientific community. Our present picture of the Flemish Cap environmental

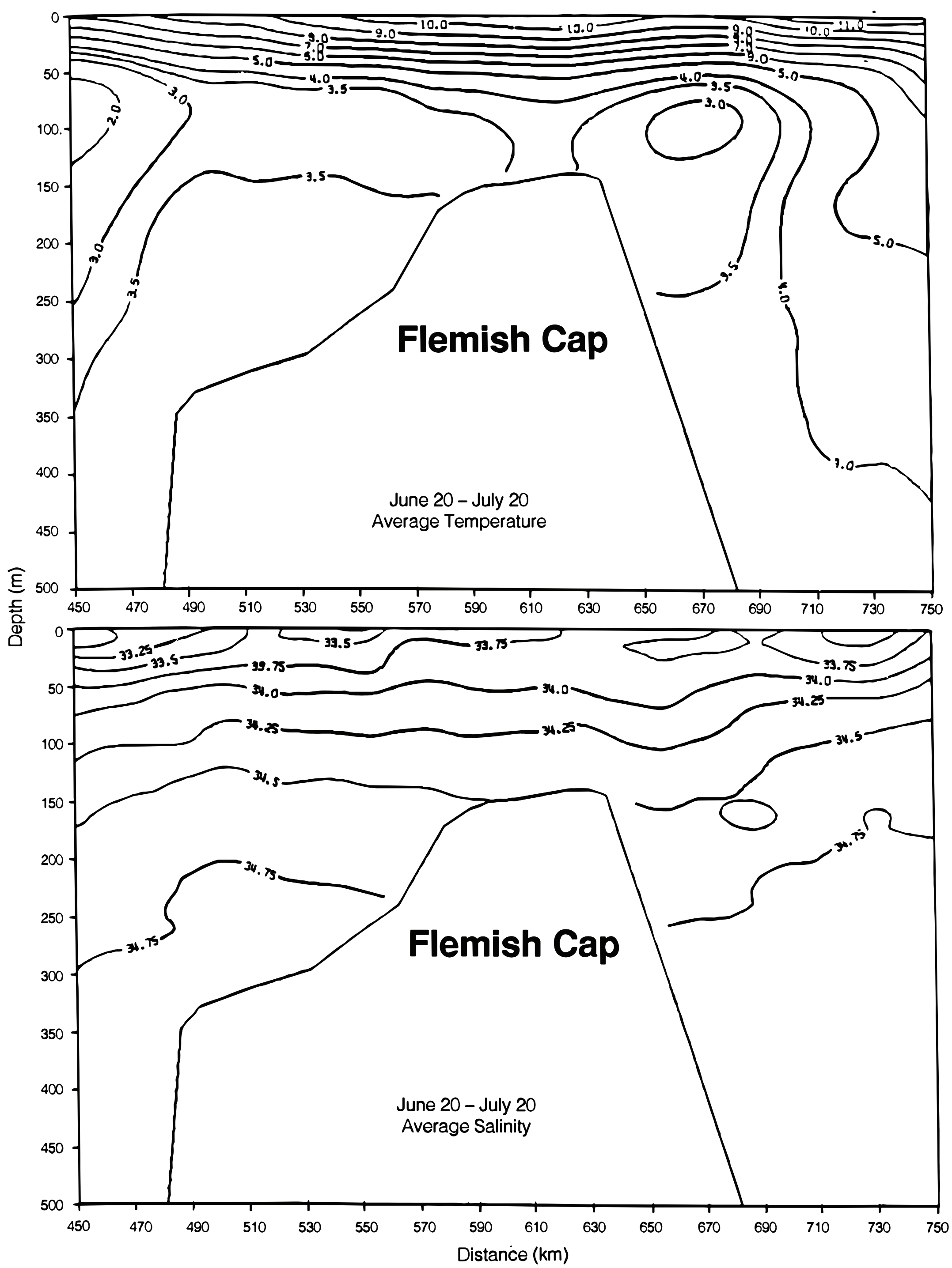

Fig. 12. Vertical distribution of average temperature (°C, upper panel) and salinity (PSU, lower panel) over the Flemish Cap based on all available historical data (from Colbourne, MS 1993).

conditions has thus become a very detailed picture. With the assistance of remote-sensing techniques, the understanding of mesoscale changes on different time scales should be possible. This could enhance strategies for the planning of research cruises.

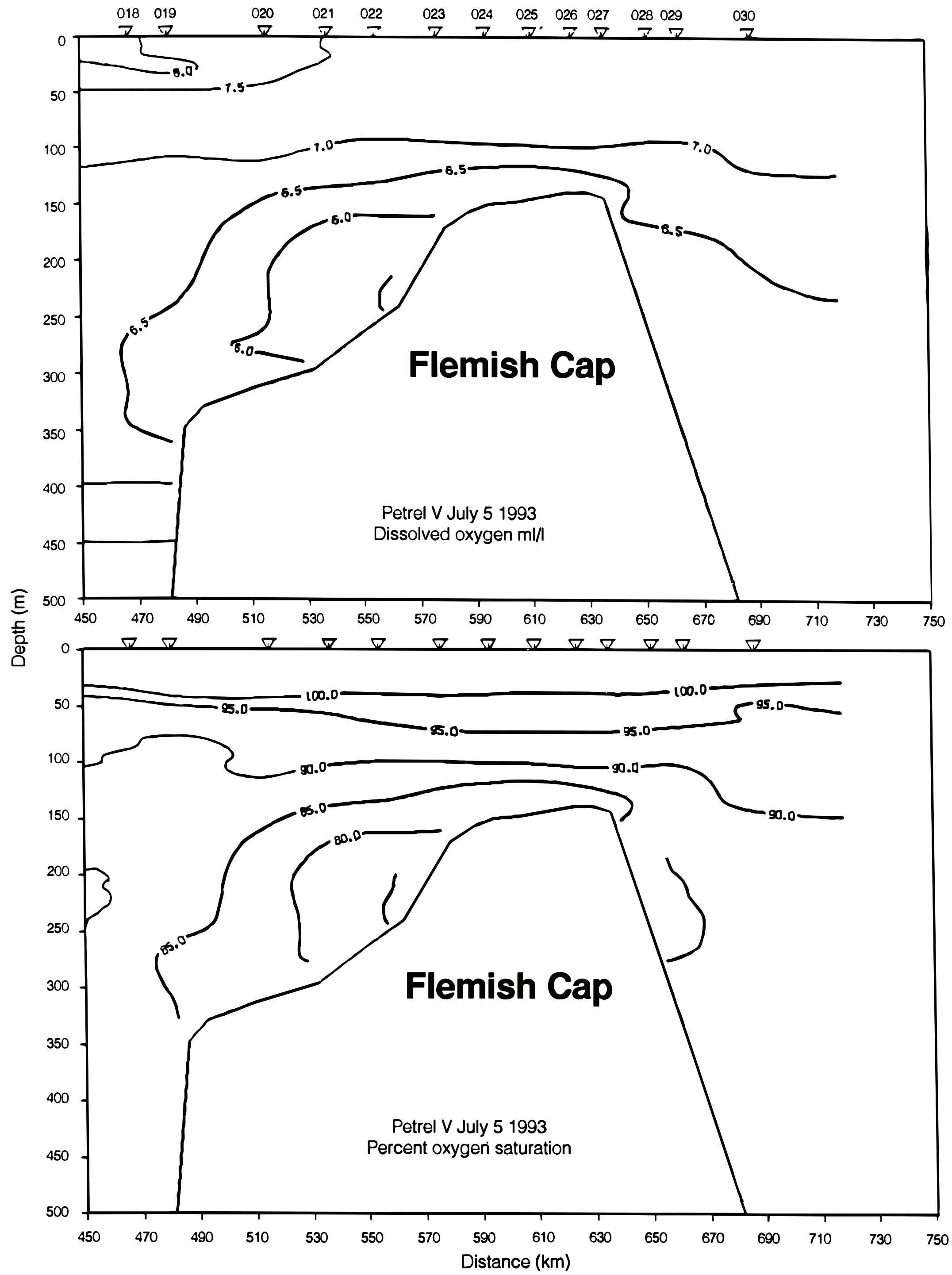

Fig. 13. Vertical distribution of dissolved oxygen concentration (ml/l, upper panel) and oxygen saturation (%, lower panel) over the Flemish Cap for early July, 1993 (from Colbourne, MS 1993).

Results based on the ASFA abstracts

Kamotskaya and Plekhanova (1975) reported on the distribution of zooplankton on the Grand and Flemish Cap Banks in relation to thermal conditions. Kudlo and Bojtsov (1979) described by means of geostrophic circulation charts based on hydrological data from surveys by USSR research vessels

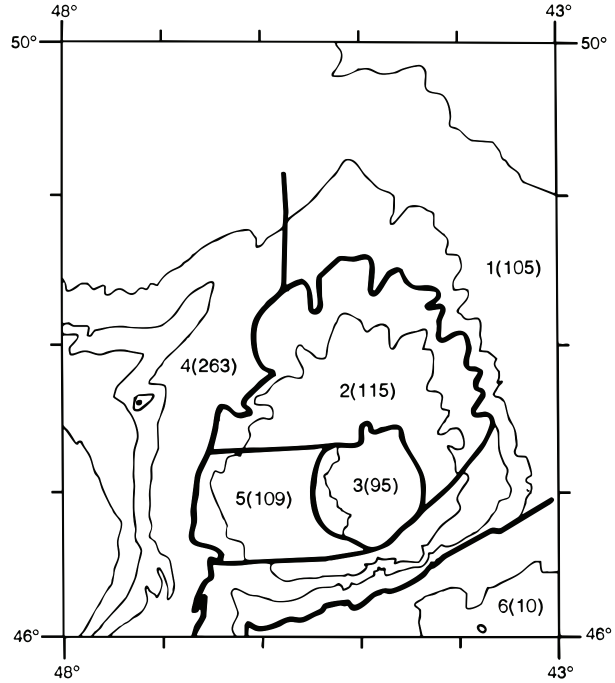

Fig. 14. Schematic of the geographic distribution of clusters with numbers of members in brackets (from Keeley, MS 1982).

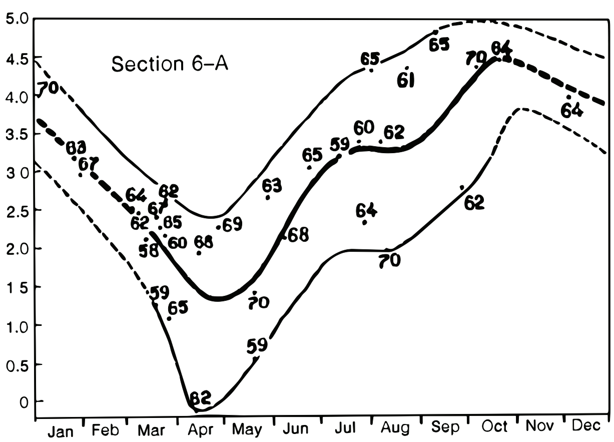

Fig. 15. Seasonal variation of temperature in the 0–200 m layer on Flemish Cap section (6-A); figures mark the years of observations (from Burmakin, MS 1971).

and the international Ice Patrol from 1955 to 1974, the existence of quasi-steady water circulation with anticyclonic motion over the central part of the Flemish Cap. The intensity of the horizontal and vertical water circulation over the central part of the bank during the period of development of cod (*Gadus morhua*) eggs and larvae, was found to be one of the main abiotic factors affecting the abundance of year-classes. It was suggested that these dynamic indices can be used to predict the relative abundance of cod year-classes well in advance of their recruitment to the commercial fishery.

According to Borovkov and Bojtsov (1978) a characteristic feature of the water circulation over the Flemish Cap Bay is the quasi-stationary anticyclonic circulation dependent on the intensity of the Labrador Current. The intensification of the circulation was usually accompanied by a temperature decline in the water column caused by the intrusion of Arctic water. The dynamic state of the anticyclonic circulation during the period of ichthyo-plankton development was described as a major factor determining the year-class strength of the Flemish Cap cod. The intensification of the circulation contributed to the accumulation of plankton and cod eggs and larvae above the Bank increasing the food supply to the larvae and the survival of young fish when they turn over to the demersal mode of life. It was suggested that the close correlation between the indices of the circulation intensity and the abundance of cod year-classes characterized by the average catches of 2-year-olds may serve as a basis for predicting the relative abundance of young cod two years in advance. By means of geostrophic circulation charts based on hydrological data from seven surveys by USSR research vessels from December 1977 to July 1978, Borovkov and Kudlo (1980) confirmed the existence of a quasi-stationary water circulation system in the Flemish Cap area, the main element of which is the anticyclonic gyre over the central part of the bank, composed predominantly of mixed water from the Flemish Cap Current. Variation in the intensity, or horizontal and vertical water movements within the gyre was observed, and the most probable factors causing this variability are discussed by the authors with particular reference to its influence on the ichthyofauna of the area. Keeley (1981) reported on analyses of all observations of potential temperature and salinity along the Flemish Cap section held by the Marine Environmental Data Service. Computations of mean conditions were made using some of the ideas of optimum interpolation. It was found that the variability in the observations was larger between the same months in different years than within the month. This resulted in a simplification of the procedure to calculate means. The values of potential temperature, salinity, and sigma theta are presented for each month. A volumetric analysis of the potential temperature and salinity by month has also been performed and is presented. A technical report was presented by Kendaris (1981a) which gave data results from three oceanographic research cruises to the Flemish Cap, carried out in March, April and May 1979. Vertical CTD profiles were obtained from 'Flemish Cap Plankton Grid' stations. Fully calibrated and processed data were interpolated to standard hydrographic depths and tabulated in

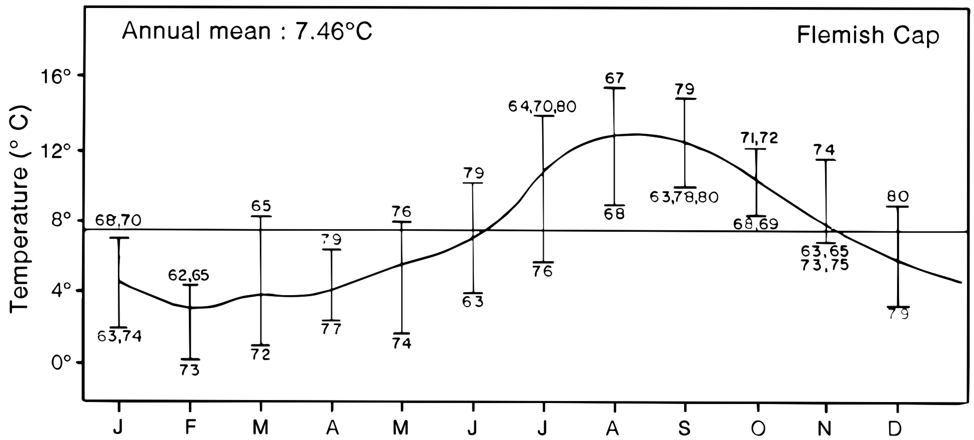

Fig. 16. Annual cycle of sea-surface temperature on Flemish Cap, 1962–81. The monthly bars indicate the extreme variations and the numbers show the years in which the event occurred (from Bailey, MS 1982).

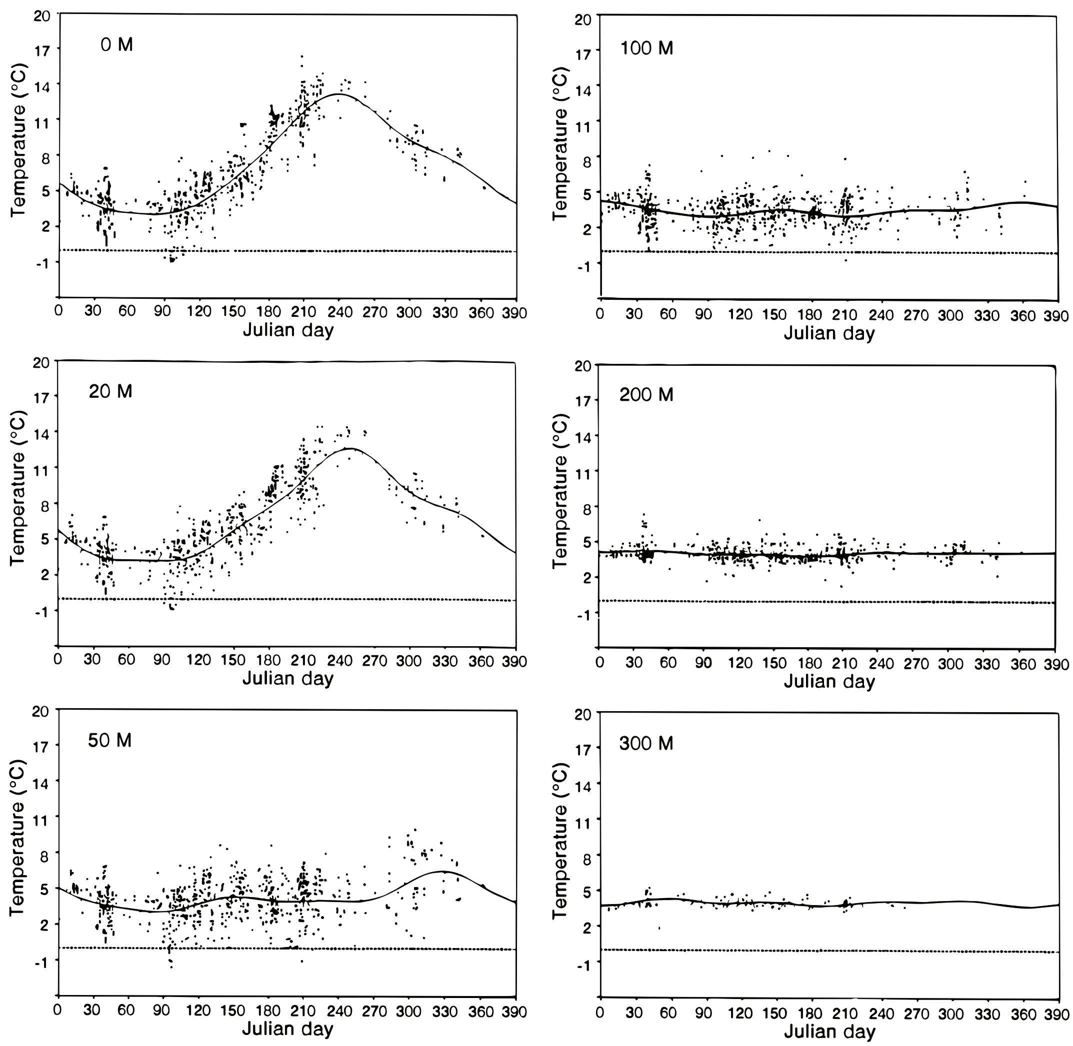

Fig. 17. Temperature values for all years at depths of 0, 20, 50, 100, 200 and 300 m for area FC1 in Fig. 2, together with the fitted regression curves (from Colbourne, MS 1993).

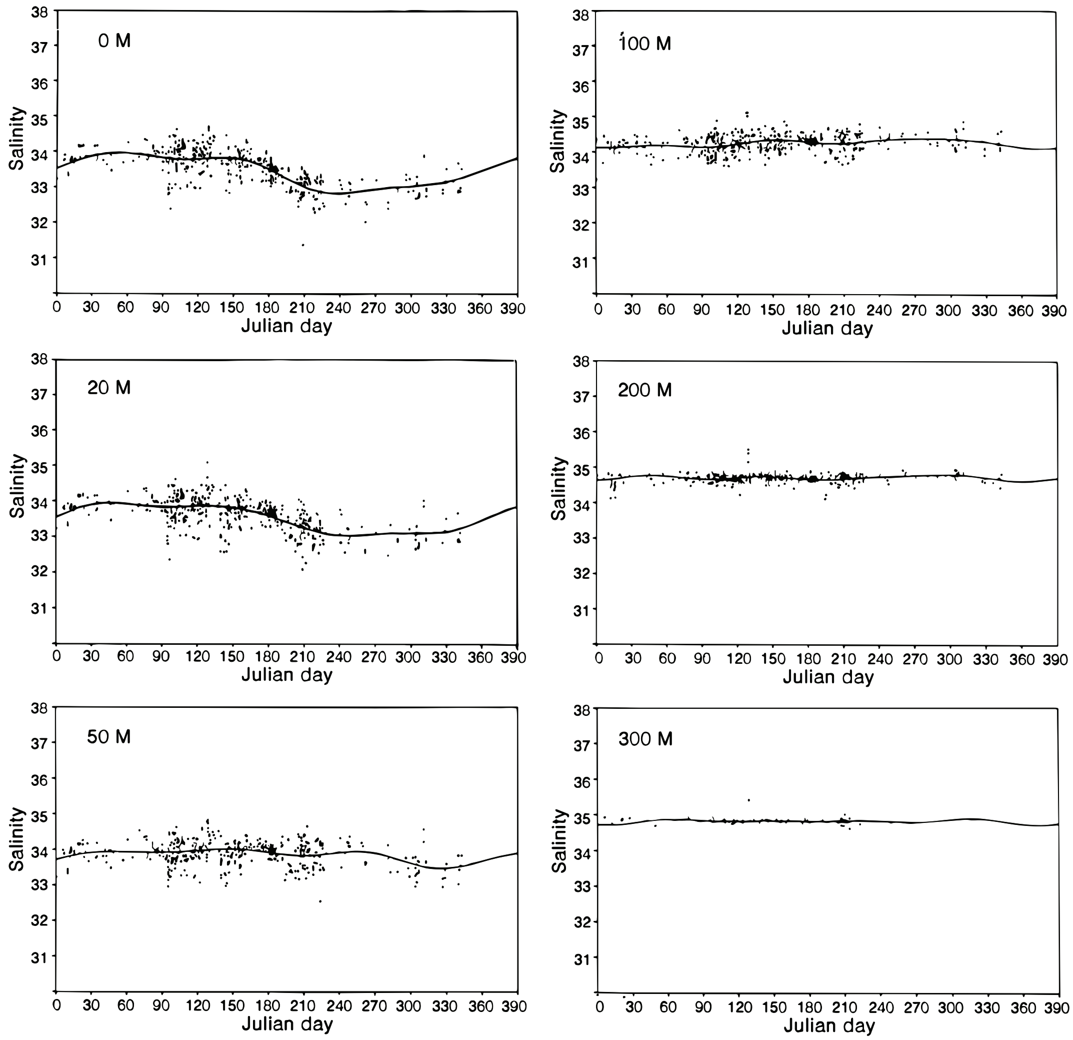

Fig. 18. Salinity values for all years at depths of 0, 20, 50, 100, 200 and 300 m for area FC1 in Fig. 2, together with the fitted regression curves (from Colbourne, MS 1993).

Appendices. Computer generated contour diagrams from each horizontal distribution of temperature, salinity and density have been provided. Observations performed in the Flemish Cap area in April, May and July 1980 were published by the same author (Kendaris, 1981b). Here too vertical CTD profiles from 'Flemish Cap Plankton Grid' stations were obtained. Fully calibrated and processed data were interpolated to standard hydrographic depths and tabulated in Appendices. Computer generated contour diagrams from each horizontal distribution of temperature, salinity and density have been provided. Keeley (1982) provided an analysis of water temperature and salinity anomalies at selected stations on the Flemish Cap section across the northern Grand Bank and Flemish Cap for the 1970–79 decade. Relative to the long-term mean conditions, the analysis indicated that the water flowing through the section was colder and fresher during the early part of the decade, followed by a return to warmer and saltier water during the later years of the decade. The change seems to have occurred sometime in 1976 or 1977.

Georgi and Schmitt (1983) investigated the spatial distribution of fine and microstructure between the Azores and Flemish Cap. The CTD data were used to calculate a conductivity-microstructure Cox number. This indicator summarizes microstructure variance from the 0.08–2.00 m vertical wavelength range. The CTD data were also used to calculate the fine structure-temperature Cox number. Finally, the fine and microstructure data were combined to calculate lateral flux and flux divergence for the

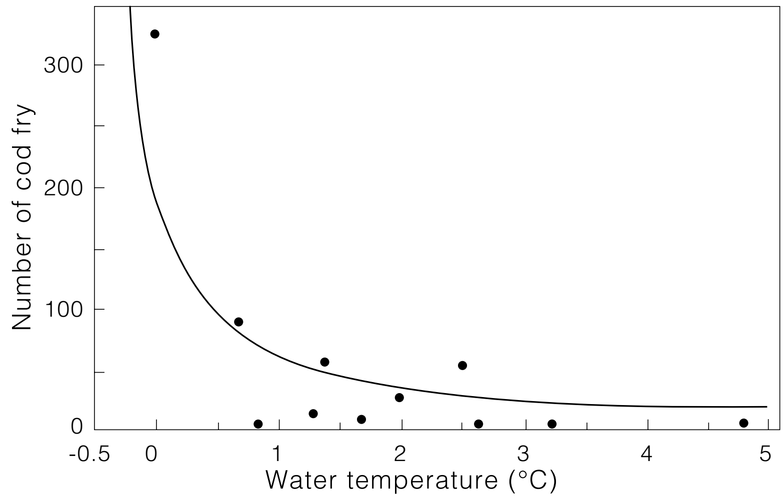

Fig. 19. Water temperature in the 0–50 m layer on the hydrographic section 4-A and index of cod year-classes strength on the Flemish Cap Bank (Arithmetic mean of average catches of yearlings and two-year-olds per trawling hour) in 1968–78 (from Konstantinov, MS 1981).

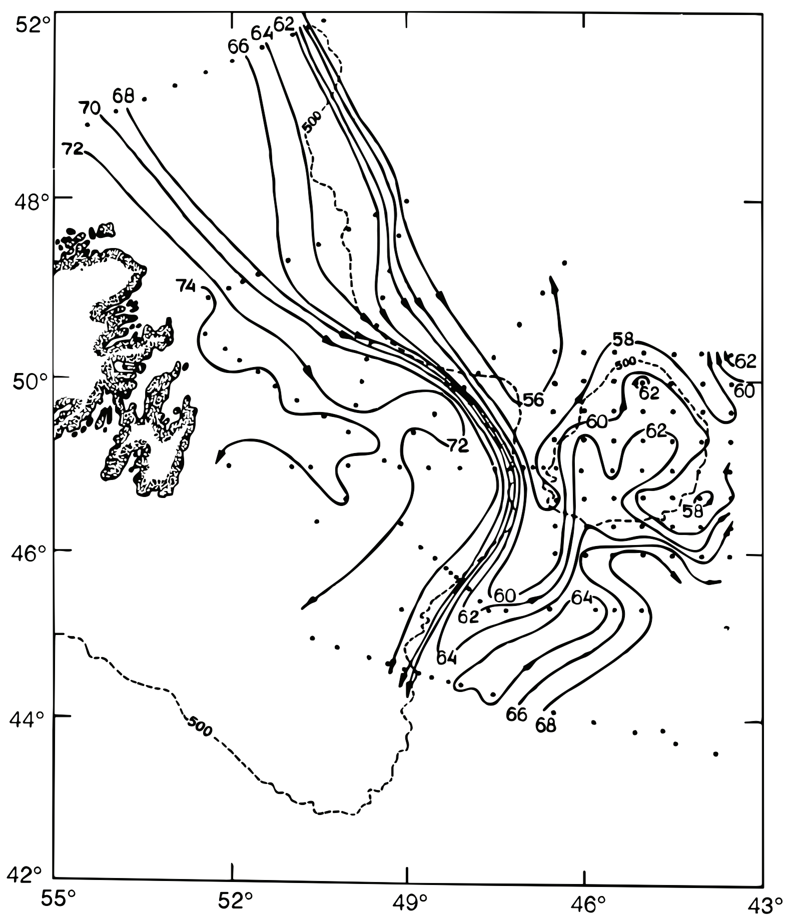

Fig. 20. Dynamic topography (dynamic centimetres) of sea surface relative to 200 dbar level in the period 13 May–11 June 1980 (from Borovkov and Kudlo, MS 1981).

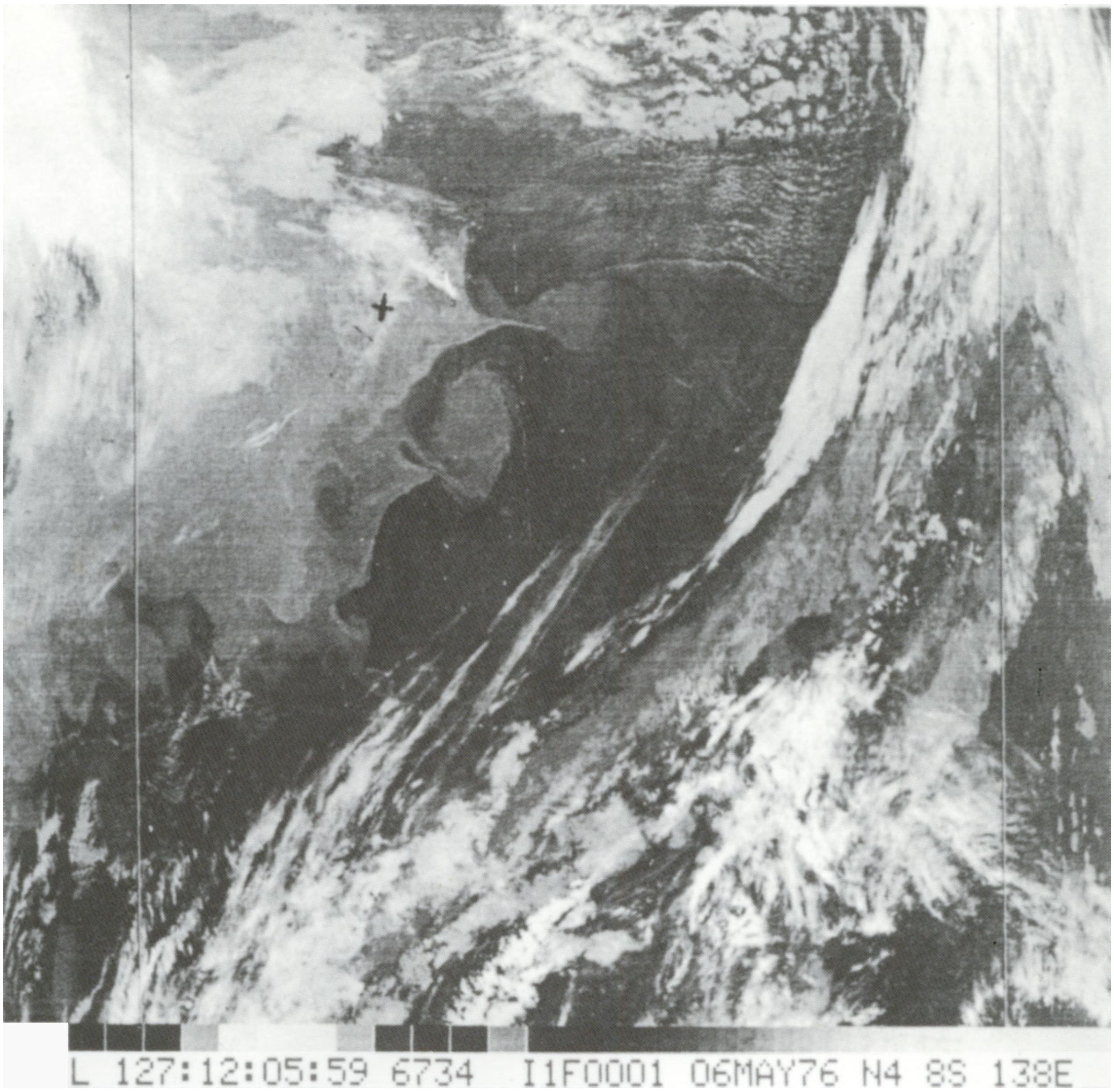

Fig. 21. NOAA Very High Resolution Radiometer (VHRR) satellite imagery of the area 46°–49°N, 43°–47°W for 6 May 1976; location of Flemish Cap is indicated by "+"; mesoscale structures of cold (gray) and warm (black) water masses are visible east and southeast of Flemish Cap (from Trites, MS 1977).

waters east of the North Atlantic Current. Holdway (1983) analyzed the effect of growth rate on the proximate composition, energy content, ovarian development maturation of Atlantic cod, *Gadus morhua*, in relation to ration size, season, temperature, age maturity, sex, and body weight for fish reared for 10 months in the laboratory over two consecutive years, 1978–80. The effect of growth rate on ovarian development and maturity was also studied for cod collected from the Gulf of St. Lawrence, the Scotian Shelf, Georges Bank, the Flemish Cap, and the N.E. Newfoundland Shelf. Relative energy and lipid content of whole cod increased with specific growth rate for all three sampling periods (November, January, March), each at 5° and 8°C. Energy, lipid, and water content were highly correlated to each other, and regressions are provided to allow for their prediction, given one of the components. Relative protein content was positively correlated with specific growth rate. Mitenev (1984) in a publication on "Fishery oceanography of the northern seas" reported on the results of USSR oceanographic research within the "Flemish Cap Project" in 1977–82. Kudlo *et al.* (1984) confirmed, with an analysis of geostrophic circulation charts based on oceanographic data from 26 surveys of Flemish Cap by USSR research vessels from December 1977 to April 1982 and a Canadian survey in January 1979, that the anticyclonic gyre is the prevailing form of water circulation which favour the retention of ichthyoplankton, mainly eggs and larvae of cod (*Gadus morhua*) and redfish (*Sebastes* spp.) on the bank. Destruction of the gyre by the passage of frequent storms result in a meandering flow across the bank, providing conditions which favour the transport of eggs and larvae away from the bank and their loss from the Flemish Cap ecosystem. Therefore, it was presented that the relative stability of the anticyclonic gyre during the period from spawning until the larvae are able to avoid massive transport by currents, is an important element in determining the success or failure of year-classes of Atlantic cod and Atlantic redfish in the area. Studies were carried out on Flemish Cap, 1978–82 by Anderson (1984) to assess fish spawning cycles, the distribution, abundance, and growth of early life stages, and their relationship to environmental factors. Redfish larvae (*Sebastes* spp.) were the most abundant fish larvae found on Flemish Cap. Redfish began releasing larvae during March, reaching an abrupt peak in late-April. Larval abundance for the study area being 6.8×10^{12} larvae. Redfish larvae first appeared in the southwest corner of Flemish Cap and within 3 weeks were found in waters throughout the area over depths >200 m. In July the survivors were concentrated over the Cap supporting the concept that Flemish Cap redfish constitute a distinct group.

Based on water temperature measurements along the 4-A hydrological section in the vicinity of the south-western slope of the Flemish Cap Bank, Konstantinov (1982) correlated water temperature with the year-class strength of cod (*Gadus morhua*) derived from the results of regular surveys of one and two-year-olds. An inverse relationship between water temperature and year-class strength was revealed. The Flemish Cap Bank is located in the southern part of cod fishing ground, where, due to negative temperature anomalies favourable conditions for survival of developing eggs and larvae seem to be constructed. Similar relationships have been established in the Northeast Atlantic. Analyses of mesoscale horizontal distributions of temperature and attenuation were performed using data from the AVHRR and the CZCS, Viehoff (1987). Primarily the situations during summer 1981 and 1983 in the area of the North Atlantic Current were investigated. Sea surface temperature distributions at strong thermal fronts were comparable with the temperature of the diurnal mixed layer. For synoptic measurements, the absolute accuracy was better than 0.4 K for time lags of ±2 days between radiometric, and for in-situ measurements the accuracy was about ±0.5 K. At the polar front the thermal pattern was moving eastward with velocities of 4.0 and 6.5 cm/s, respectively, with a relative persistence of mesocale pattern of 14 days. The sea-surface temperature distributions have shown considerable time variability, especially east of Flemish Cap and at the Mid-Atlantic Ridge south of 50°N. Based on midwater-trawl catches of glacier lanternfish (*Benthosema glaciale*) over the slopes of Flemish Cap and eastern Grand Bank in the Northwest Atlantic, Albikovskaya (1988) reported that these catches consisted mainly of age-groups 3 and 4, most of which were in the 45–60 mm SL range. The smallest and largest specimens were 27 and 72 mm SL, and males were somewhat more numerous than females. The pattern of gonad development in females indicated that spawning probably occurs intermittently in early-autumn and winter, with the subsequent occurrence of larvae being coincident with the period of high zooplankton abundance (April–May). Growth was evidently rapid during the first 2–3 years of life and decelerates markedly thereafter, with the lifetime being at least 5 years. The sonic-scattering layer (mainly *B. glaciale* and other myctophids) remained at 300–400 m (3.5°C) with little daily vertical movement, due presumably to the overlying very sharp temperature gradient. Anderson (1989) compared the timing of primary and secondary production cycles and their effect on larval fish feeding, growth, and survival between two years on Flemish Cap (47°N, 45°W). Colbourne (MS 1993a) examined oceanographic data around the Flemish Cap area to compare conditions during the last few years to the long-term average. The results indicated that the large oceanographic anomalies experienced over the continental shelf in Atlantic Canada also existed around the Flemish Cap area during the same time periods. In particular, temperatures have been up to 2.0°C below normal in the upper 100 m of the water column since the late-1980s and about normal in water depths below 300 m. These anomalies were generally associated with strong winter northwesterly circulation, colder than normal air temperatures and heavy ice years in the Northwest Atlantic. In addition, the presence of a general anticyclonic circulation around the Flemish Cap was confirmed on a July 1993 cruise, using an acoustic doppler current profiler. In a report, Colbourne (MS 1993b) described the state-of-the-ocean over the Grand Bank of Newfoundland during mid-spring 1993 with a comparison to the mean conditions based on all available historical data. The report presented a subset of the data collected on the first oceanographic cruise of the 1993 field season funded by the Northern Cod Science Program (NCSP) aboard the CSS PARIZEAU. This study was intended to provide information on oceanographic conditions during the inshore migration of northern Atlantic cod (*Gadus morhua*) to the bays along the east coast of Newfoundland at approximately one month intervals prior to, during, and after the peak cod migration. It was intended to make oceanographic measurements along transects running from the inshore areas of Conception Bay, Trinity Bay and Bonavista Bay and offshore to the shelf edge, however ice conditions prevented working north of Cape St. Francis. Instead the survey was conducted from the inshore areas along the Avalon Peninsula from Station 27 south to Cape Race and offshore to the shelf edge along the standard NAFO Flemish Cap transect. The survey then proceeded southwest along the shelf edge to Carson Canyon and shoreward to Cape Race. A final transect running from Cape Race across the northern Grand Banks in a northeasterly direction to the ice edge was conducted. Measurements along the transects included vertical profiles of current, temperature, salinity, chlorophyll and dissolved oxygen. In addition water samples were collected at each station for salinity, chlorophyll, oxygen and biological analysis. Anderson (1994) revealed that eggs and nauplii of the copepod *Calanus finmarchicus* were the preferred prey types of redfish *Sebastes* spp. larvae, whereas *Oithona* spp. copepodites were not, even though they were within the preferred size range. Significant seasonal and annual differences in larval diet of redfish resulted from differences in the availability of preferred prey. Seasonally, feeding was related to the succession of the spring dominance of *C. finmarchicus* to summer dominance of *Oithona* spp. Interannually, feeding was related to differences in the timing of spring spawning and temperature-dependent development of *C. finmarchicus*. Earlier spawning and faster development of *C. finmarchicus*, dependent on warmer water temperatures, resulted in poorer feeding conditions for redfish larvae. Under these conditions redfish larvae; (1) ate predominantly nauplii and copepodites of *Oithona* spp.; (2) ate less food by weight; (3) had lower relative body condition; and (4) there was a delayed size at metamorphosis from larvae to pelagic juveniles. Total prey concentrations between years did not determine better feeding and condition of redfish larvae, whereas the availability of preferred prey types did. Specifically, a lower abundance of *C. finmarchicus* nauplii resulted in better feeding conditions than a higher abundance of *Oithona* spp. copepodites. These results emphasized that measuring total prey biomass within preferred prey sizes was not sufficient when evaluating larval redfish feeding conditions. There was a switch in diet for pelagic juveniles to include *Oithona* spp. copepodites as preferred prey, in addition to copepod eggs and nauplii. This switch in diet coincided with changing prey availability due to the seasonal succession of zooplankton on Flemish Cap. Metamorphosis from larvae to juveniles at smaller sizes and younger ages was hypothesized to be advantageous to annual survival of redfish due to an increased foraging ability. Frank *et al*. (MS 1994) demonstrated that we are now witnessing a concurrent southward and eastward extension of capelin (*Mallotus villosus*) distribution, particularly on the eastern Scotian Shelf and Flemish Cap. These latest events coincided with the occurrence of atmospheric and oceanic extremes in the Labrador Sea/Newfoundland Shelf region and the Gulf of St. Lawrence. In general, cold air temperatures, heavy sea ice and cold water temperatures have prevailed in these regions during the past 3–5 years. They document these recent unusual occurrences of capelin on the eastern Scotian Shelf and Flemish Cap in the context of their historical occurrences in these areas and in relation to recent hydrographic events. Myers and Pepin (1994) examined the hypothesis that recruitment is more variable in populations on isolated offshore banks than nearby shelf populations. Recruitment of cod (*Gadus morhua*) and American plaice (*Hippoglossoides platessoides*) on Flemish Cap was more variable than in any comparable population. Perez-Gandaras and Casas (MS 1994) studied the otoliths of different Flemish Cap Atlantic cod (*Gadus morhua*) cohorts for the period 1980–89. It was shown that the annual classes of Flemish Cap cod from 1979 to 1989 provided no evidence of migration. This conclusion was based on a study of their otoliths following the characterization of the rings applied to Greenland cod. Bowering and Brodie (1994) determined distribution, age and growth, and sexual maturity of American plaice (*Hippoglossoides platessoides*) on the Flemish Cap from 1978 to 1985. American plaice were distributed mainly in the shallower areas, generally in the central, southern and southwestern areas of Flemish Cap. Densities were much lower on average than in the adjacent Grand Bank area. There was no size selective distribution by depth or temperature. Examination of otoliths revealed that females grew at a faster rate than males after age 3. The maximum age recorded was 15 years, which was considerably lower than the value for adjacent stocks of American plaice. In many years the population was dominated by no year-class, which comprised up to 68% of the catch numbers.

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