

# Northern Shrimp (*Pandalus borealis*) on Flemish Cap (NAFO Division 3M) – Oceanography, Fishery and Biology

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## Abstract

The purpose of this paper is to consolidate information presented to the Scientific Council of NAFO during 1993–95 on northern shrimp (*Pandalus borealis*) on Flemish Cap. Also included are sections on oceanography of the area, general biology of the species and by-catch of fish in the commercial fishery for shrimp.

Oceanographic data describe the habitat in relation to bathymetry, temperature, salinity and circulation. Shrimp distribution, determined from research surveys, commercial fishery data and stomach contents of cod (*Gadus morhua*), occurred within depths of 200–600 m where temperatures and salinities were approximately 4.0°C and 34.0 PSU, respectively. An anticyclonic gyre over the centre of the Cap dominated the circulation, providing a mechanism for the retention of shrimp larvae in the area. The bottom trawl fishery for shrimp, which began in 1993, increased rapidly through the participation of vessels from several nations. Catches decreased from about 28 000 tons in 1993 to 24 000 in 1994 but increased to 33 000 in 1995. Fishery regulations initially dealt with limiting by-catch, primarily redfish (*Sebastes* sp.), and concerns about discard mortality led to mandatory use of sorting grates in shrimp trawls in 1994. A substantial decline in redfish by-catches in 1995 was coincident with a decrease in the bar spacings of sorting grates and with an increase in individual size and decrease in numbers of a strong redfish year-class.

Catch-effort data from the fishery (1993–95) and research trawl surveys (1988–95) provided indices of biomass which showed a large increase between 1990 and 1992 and a decline, thereafter. Biological sampling for length, sex and maturity from both sources were used to determine age and growth. Shrimp on the Flemish Cap show life history characteristics similar to warm water populations at early life stages and to cold water populations later in life, consistent with influences of both the Gulf Stream and Labrador Current in the Flemish Cap area. Several species of finfish in the Flemish Cap community are predators and/or competitors of shrimp but relationships between the abundance of shrimp and the abundance of any other species have not been investigated.

*Key words:* biology, by-catch, Flemish Cap, northern shrimp, oceanography

## Introduction

Northern shrimp (*Pandalus borealis* Krøyer, 1838) has long been considered the primary cold-water shrimp resource in the Northwest Atlantic (Longhurst, 1970). Statistics from the Northwest Atlantic Fisheries Organization (NAFO) Convention Area show that recent annual catches of these shrimp have been the highest reported for all marine crustacea (NAFO, 1995a).

The occurrence of northern shrimp on Flemish Cap (NAFO Division 3M) (Fig. 1a) has been known for many years. Squires (1970) reported the spe-

cies "in considerable numbers ... near the Flemish Cap", thereby contributing to the knowledge of its widespread distribution throughout the Northwest Atlantic (see below and Allen, 1959). Detailed information on the distribution and biology of shrimp in this area was lacking until 1988 when a European Union (EU–Spain) research survey caught them frequently in a lined, groundfish trawl (Vazquez, MS 1989). Similar surveys, conducted annually, have provided a valuable time series of information on recent changes in distribution, relative biomass and demographic structure of the shrimp (Sainza, MS 1995). Additional data on distribution and biology have been obtained from

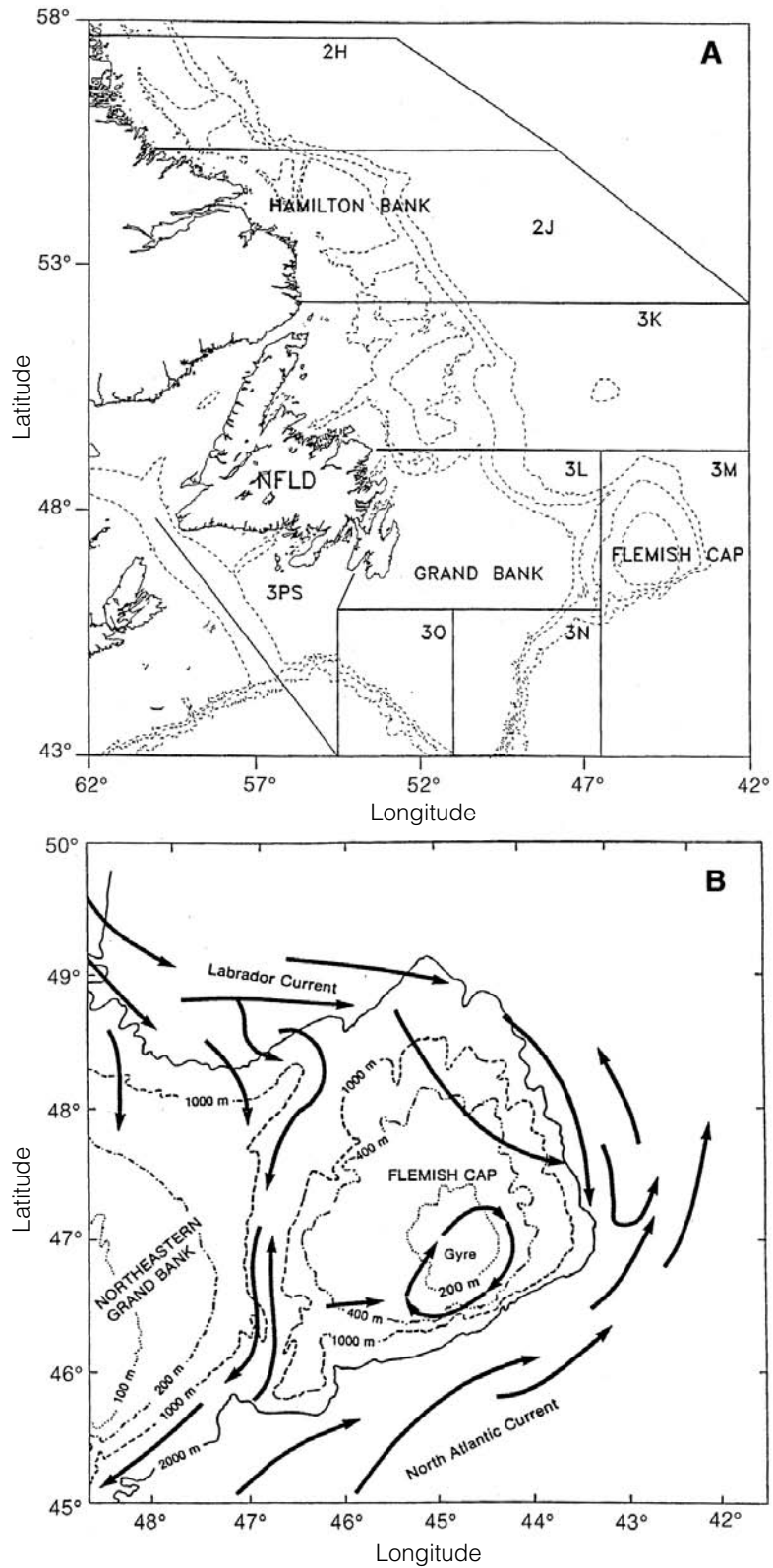


Fig. 1. (A) Location map of the Flemish Cap (bathymetry lines are 300, 1 000 and 2 000 m) and (B) major circulation features (adapted from Anderson, 1984).

commercial fishing vessels of several nations since the spring of 1993. In this paper, we review and consolidate information relevant to northern shrimp on Flemish Cap from published literature and reports presented at NAFO Scientific Council meetings in 1993, 1994 and 1995. New analyses of the spatial distribution of the fishery and finfish by-catch also are provided.

### The Physical Environment of Flemish Cap

The Flemish Cap is a large, relatively deep bank located east of the Grand Bank of Newfoundland at about 47°N, 45°W (Fig. 1A). Minimum water depth is about 150 m. The diameter of the bank at the 500 m isobath is about 200 km for a total area of approximately  $3.0 \times 10^4$  km<sup>2</sup>. To the west, the Cap is separated from Grand Bank by the Flemish Pass with water depths of 1 000–1 100 m. At the 2 000 m isobath the bank appears as an eastward extension of the Newfoundland Continental Shelf Slope.

The water mass over Flemish Cap is a mixture of Labrador Current water and North Atlantic Current water, producing water temperatures that are higher than those over the adjacent Grand Bank within similar depth ranges. For example, at depths of 100–150 m bottom temperatures over the Grand Bank are generally less than 0.0°C compared to about 3.0 to 4.0°C over the Flemish Cap (Colbourne and Senciall, 1996). Flemish Cap is relatively ice free. The ice edge encroaches briefly during February and March of severe ice years.

### Circulation

Two major current systems dominate the circulation around the Flemish Cap. The offshore branch of the Labrador Current transports cold, low salinity water to the south through the Flemish Pass and to the east and southeast around the northern and eastern slopes of the bank. The North Atlantic Current transports warmer, high salinity water to the northeast along the southeast slope of Grand Bank and the Flemish Cap (Fig. 1B). The circulation over the centre of the Cap is dominated by a topographically induced anticyclonic (clockwise) gyre (Kudlo *et al.*, 1984; Ross, 1981). The stability of this circulation pattern is strongly influenced by atmospheric forcing at weather band frequencies. Kudlo *et al.* (1984) have shown that there are frequent cross-shelf meander type flows, the frequency of which is greatest during the winter months when

the mean wind speed is greatest. Variations in the Labrador current, the Gulf Stream and the North-west Atlantic Current likely play important roles in the circulation in the area.

A survey in July 1993, using acoustic Doppler current profilers (ADCPs), has provided a more detailed view of the currents (Colbourne, MS 1993). In the Flemish Pass, the offshore edge of the Labrador current, up to 200 m deep, flowed at about 15 cm/s in a general southerly along-shelf direction (Fig. 2). Over the Flemish Cap itself the circulation was predominately anticyclonic with northward currents of 5–15 cm/s over the western portion of the bank and southward currents of 5–15 cm/s over the eastern portion. These data suggest a recirculation time of roughly 10 weeks along the 500 m isobath (gyre width of approximately 200 km) at an average current speed of about 10 cm/s. Further up on the bank, within the 200 m isobath, recirculation times were in the order of 50 days at 10 cm/s.

Recirculation times calculated from synoptic observations are not necessarily equivalent to residence times of the water mass over the Cap. Available data suggest that residence times are significantly less than recirculation times. For example, Loder *et al.* (1988) used drifter tracks to calculate mean recirculation times of 67–78 days along the 400 m isobath with residence times of about 32 days. This indicates that variability in the meandering cross-bank flow may be the most significant circulation feature from a biological perspective. As postulated by Kudlo and Borovkov (1977) and by Kudlo and Boytsov (1979), the stability of the circulation patterns around the Flemish Cap may influence the retention of ichthyoplankton on the bank and is probably a factor in determining the year-class strength of various species such as cod, redfish and shrimp. This hypothesis has not been tested (Lilly 1987).

### Temperature and Salinity

Seasonal changes in temperature and salinity over central Flemish Cap along the 47°N line were calculated by Colbourne and Senciall (1996) from data available for 1931 to 1995 (Fig. 3). The water column is nearly isothermal at about 4.0°C from January until April and remains at about 4.0°C throughout the remainder of the year at depths below approximately 100 m (Fig. 3A). Seasonal warming of the upper layer commences by early-

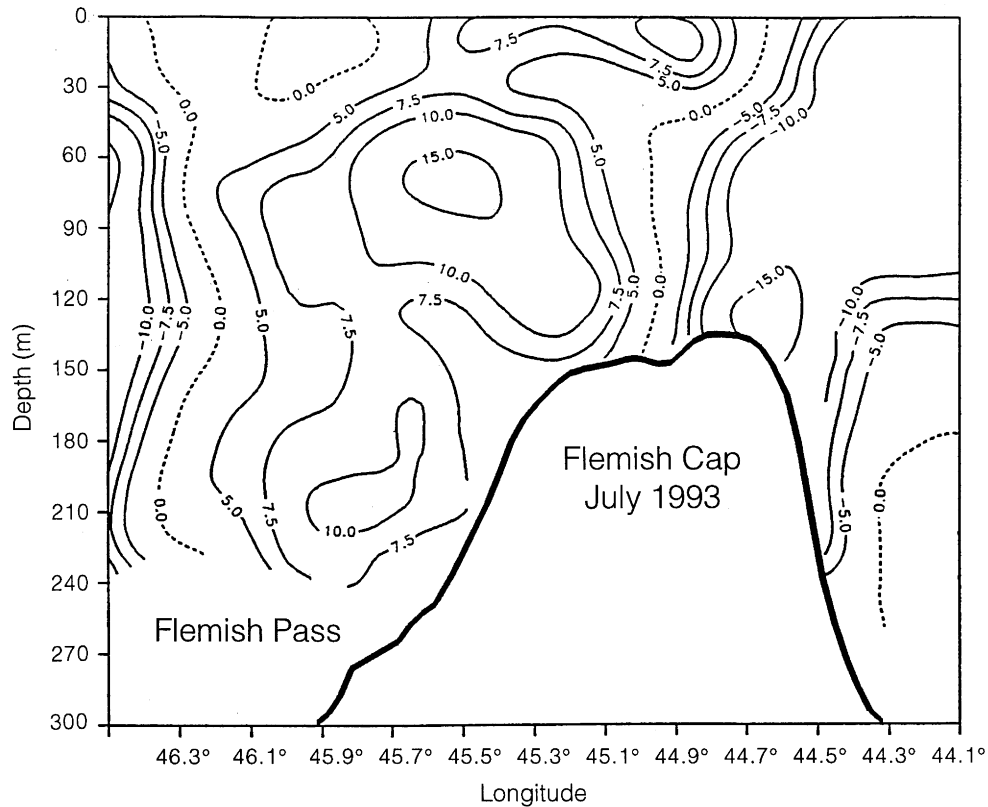


Fig. 2. Vertical cross-section of the north-south current field (cm/s) over the Flemish Cap along 47°N during July 1993. Negative currents are southward, positive currents northward (from Colbourne, MS 1993).

May and progresses at a rate of about 0.1°C per day until late-August or early-September when it reaches a maximum of between 12.0 and 13.0°C. The seasonally heated upper layer reaches a maximum depth of about 80 to 90 m by late-November by which time the surface layer is cooling. In January, salinity ranges from about 33.5 practical salinity units (PSU) in the upper water column to about 34.25 PSU near the bottom (Fig. 3B). Conditions tend to be isohaline near 34.0 to 34.25 PSU from March until June after which the upper layers experience a gradual freshening, reaching a minimum of 33.5 PSU by mid-July. At depths greater than 90 m, salinities remain at about 34.0 to 34.25 PSU throughout the year.

The vertical distribution of the July average temperature and salinity over the Flemish Cap along the standard 47°N transect based on all available historical data from 1961 to 1990 (Colbourne, MS 1996) are shown in Fig. 4. The average temperature ranged from about 10 to 11°C near the surface to 4.0°C at 50 m depth. In deeper water (50 m to the bottom), the temperature ranged from 2.0 to

3.5°C in the Flemish Pass area, in the offshore branch of the Labrador Current, and from 3.5 to 5.0°C east of the bank where the influence of the Gulf Stream was evident (Fig. 4A). The corresponding July average salinities generally ranged from 33.5 PSU near the surface to 34.75 PSU near the bottom over the Flemish Cap in water depths of about 300 m. In water depths greater than 300 m salinities were generally greater than 34.75 PSU (Fig. 4B).

Temperature and salinity anomalies at standard depths over the period 1970–94 were constructed by subtracting a least squares fit to the seasonal cycle from each observation (Colbourne, MS 1993). This time series of residuals was then low pass filtered to highlight interannual variations and to suppress the high frequency variations shorter than a season. The time series of temperature anomalies at depths down to at least 100 m (Fig. 5A) were characterized by 3 major cold periods: most of the 1970s, the mid-1980s and the late-1980s to early-1990s. The cold period, beginning around 1971, continued until 1977. Temperature anomalies

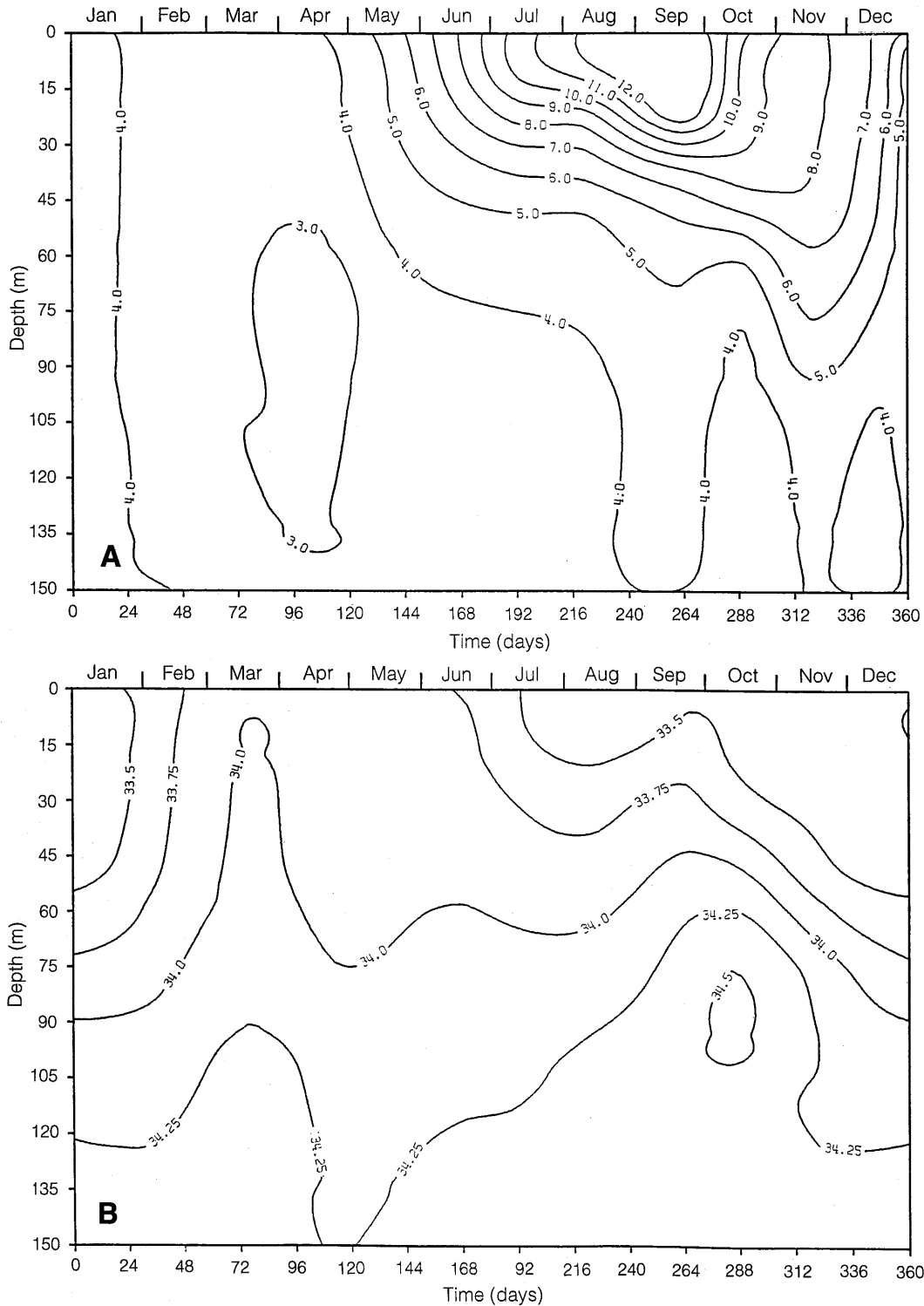


Fig. 3. Time series of the monthly mean (A) temperature and (B) salinity over the central Flemish Cap along 47°N based on all available historical data from 1931–95 (Colbourne and Senciall, 1996).

reached values of 1.5°C below normal over the upper water column in 1974. From 1978 to 1984, the temperature anomalies showed a high degree of

variability in the upper water column with a tendency towards positive anomalies. By 1985, intense negative temperature anomalies had returned with

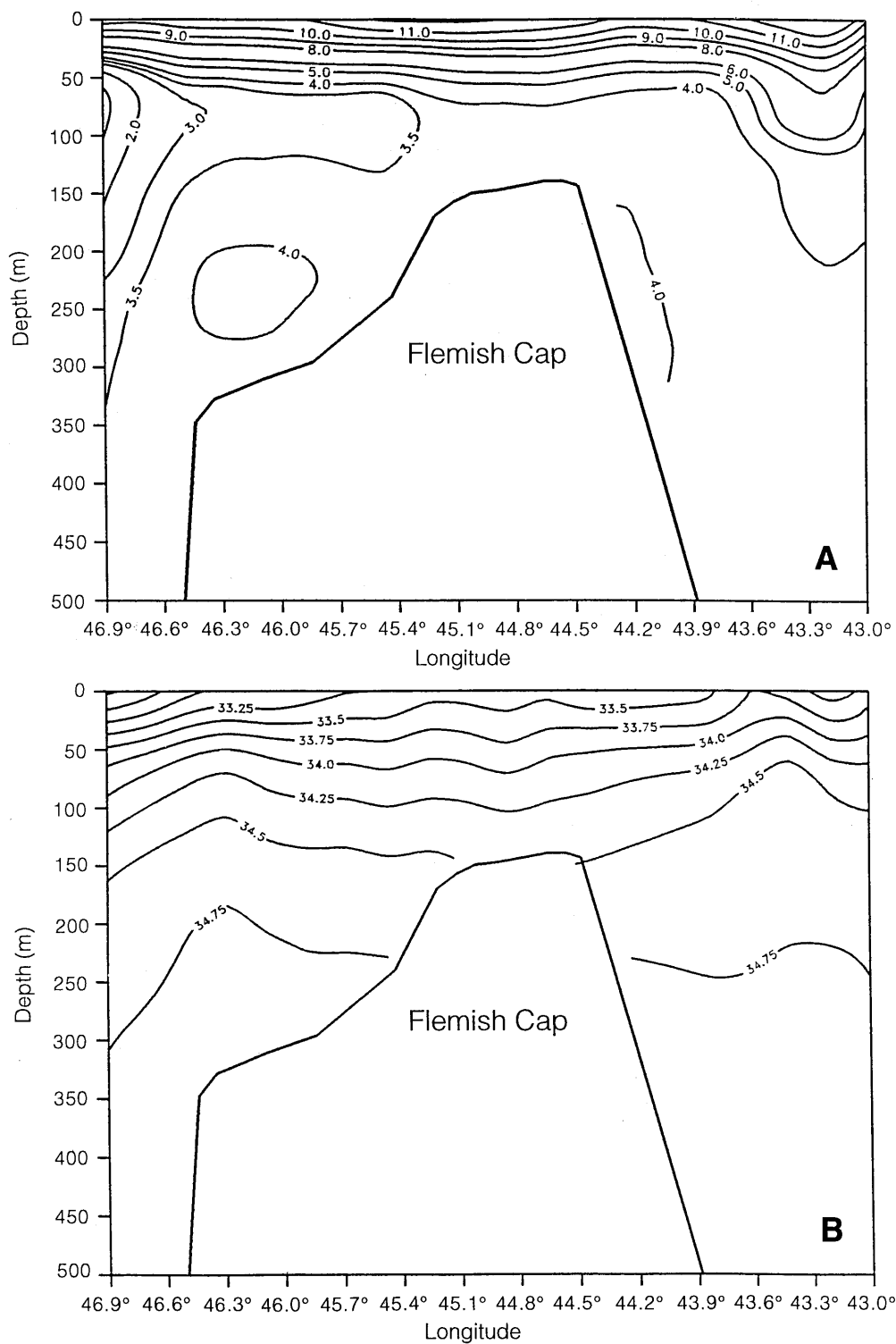


Fig. 4. Vertical distribution of the average (A) temperature and (B) salinity over the Flemish Cap in July along 47°N based on all available historical data from 1961–90 (from Colbourne, MS 1996).

peak amplitudes reaching 3.0°C below normal at depths to 50 m. This cold period moderated briefly in 1987 but continued to the summer of 1993 with anomalies reaching 2.0°C below normal by July of 1993. The time series of salinity anomalies (Fig. 5B) showed large, fresher than normal conditions from 1971 to 1976 and from 1983 to 1986 in the upper 100 to 200 m of the water column with peak amplitudes reaching 0.5 PSU below normal. Salinities during the early-1990s appeared to be about normal. Like the temperature anomalies, the salinity anomaly amplitude was maximum in the upper mixed layers where the effect of ice melt is the largest. Anomalies of both temperature and salinity were very small at depths greater than 200 m.

### General Biology of *P. borealis*

In the Northwest Atlantic, *P. borealis* occurs from Georges Bank (about 41°N) to Davis Strait (about 72°N), and supports fisheries in the following areas: Gulf of Maine, Scotian Shelf, Gulf of St. Lawrence, Newfoundland-Labrador and both sides of Davis Strait. Distribution continues through East Greenland, Iceland and the Northeast Atlantic, including the Norwegian, Barents and North Seas (Parsons, MS 1982). The species also has been reported from the Pacific in areas off British Columbia (Butler, 1980), Japan (Ito, 1976) and eastern Russia (Kitano and Yorita, 1978), although Squires (1992) recognized the Pacific form as a separate

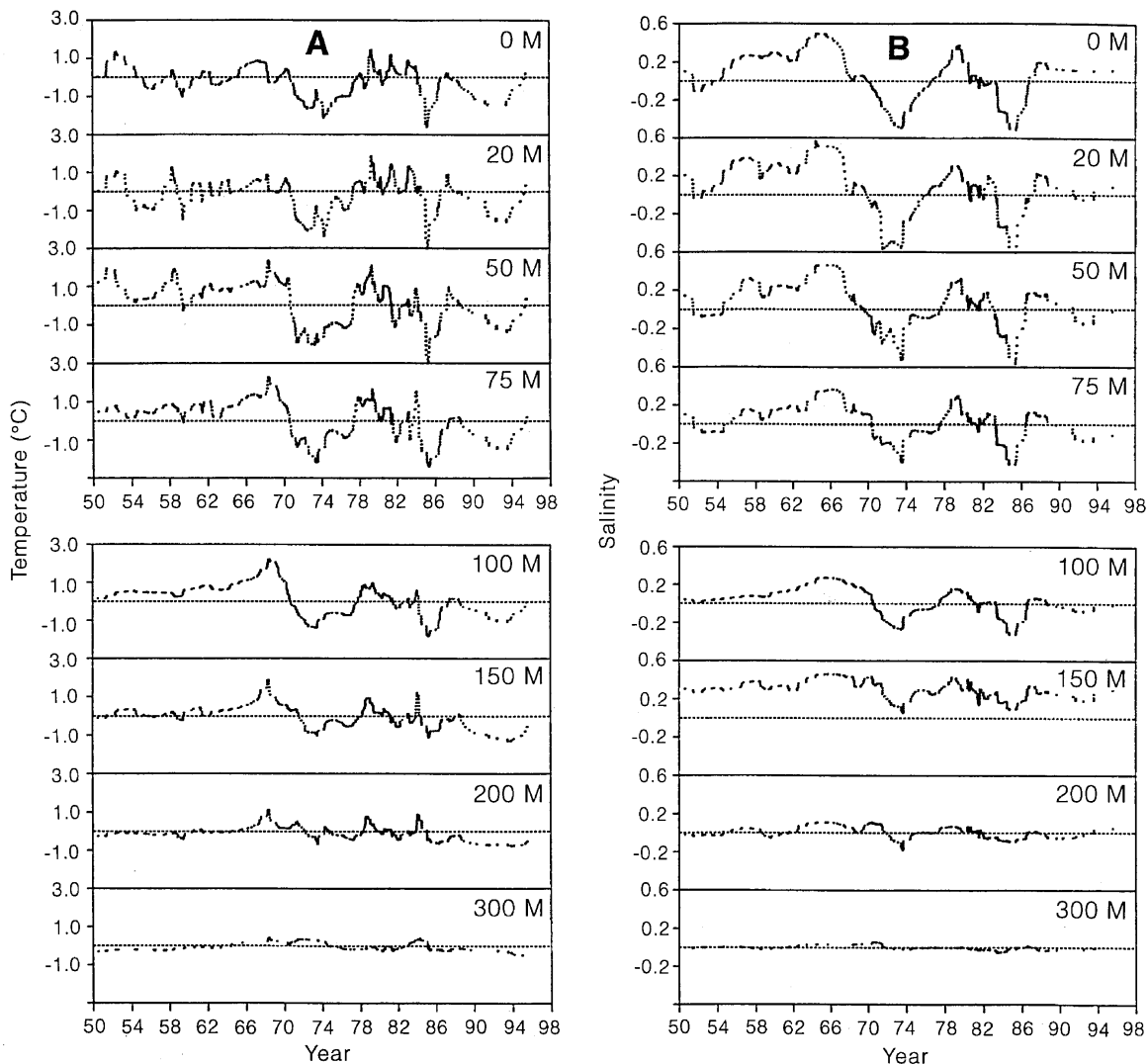


Fig. 5. Time series of (A) temperature and (B) salinity anomalies on the Flemish Cap at standard depths (adapted and updated from Colbourne, 1993).

species, *Pandalus eous*, based on morphological differences in adults and size differences in larvae.

Allen (1959) observed that substrate, temperature, salinity and depth are factors that influence the distribution of *P. borealis*. The species is usually associated with soft, muddy substrates (Butler, 1971) and has been found in temperatures generally between 3° and 8°C (Rasmussen, 1965), but occasionally as cold as -1.68°C and as warm as 11.13°C (Allen, 1959), in salinities between 25.9 and 35.7 PSU (Butler, 1971) and in depths from less than 10 m to greater than 1 300 m (Butler, 1971).

The species is a protandric hermaphrodite (Berkeley, 1930). It matures as a male as early as age 1 and functions as such for one or more years. It then passes through a transitional stage when sex change occurs and spends the rest of its life as a female. Age at sex change is variable within and among populations. In some, the male phase is suppressed (Butler, 1971) while, in others, sex inversion from male to female might not occur (Squires, 1968).

The species migrates vertically, especially at night (Allen, 1959). This migration has been associated with a pelagic phase of feeding based on the occurrence of pelagic prey species in stomachs (Horsted and Smidt, 1956; Barr, 1970; Berenboim, 1981; Wienberg, 1981; Hopkins *et al.*, 1993). However, shrimp are also known to feed while on the bottom.

Biological differences among populations are evident along a latitudinal gradient. Generally, northern populations exhibit a slower rate of growth, delayed maturation and greater longevity (Rasmussen, 1953; Horsted and Smidt, 1956; Squires, 1968; Apollonio and Dunton, MS 1969; Haynes and Wigely, 1969; Shumway *et al.*, 1985). The mature male phase may last for several years. Females in northern populations have been aged to 8+ years and attain maximum sizes which are greater than those seen in some southern areas.

### The Shrimp Fishery

The fishery for northern shrimp on Flemish Cap began in late-April, 1993 when two Canadian vessels were granted exploratory permits to fish the species in NAFO Div. 3M. The only known commercial activity targeting shrimp prior to 1993 was

in 1990 when two Canadian vessels fished unsuccessfully in April and May.

### Fishing Technology

Quantitative information on the relative fishing power of ships used in this fishery by the different nations is lacking. Some nations operate small, inefficient vessels which might have been designed originally for fishing species other than shrimp. Such vessels report daily catches usually in the range of 2 to 4 tons. Other vessels are technologically advanced and in some instances were built specifically to harvest shrimp. These often catch 10 or more tons a day. All vessels tow otter trawls with small mesh to retain the shrimp. Some of the larger vessels tow two complete trawls simultaneously. This was first reported for an Icelandic trawler in 1994 (Skuladottir, MS 1994) and later for several Greenlandic (Siegstad and Hvingel, MS 1995) and Faroese vessels (NAFO, 1995b). Sorting grates to minimize by-catch were made mandatory by the NAFO Conservation and Enforcement Measures for this fishery beginning in 1994 and maximum bar spacing was reduced from 28 mm in 1994 to 22 mm in 1995 (see below).

### Regulations

No NAFO regulations were imposed on the shrimp fishery in Div. 3M in 1993 but individual nations might have applied some for their own vessels. The rapid expansion of the fishery prompted NAFO Scientific Council to conduct an initial assessment of the resource in September, 1993. The Council concluded that data were insufficient to provide a basis for the calculation of a TAC but advocated a cautious approach to exploitation, given the potential for high fishing mortality. No preemptive or precautionary catch or effort limits were recommended or implemented for 1994 by the Fisheries Commission. In its considerations in 1993, Scientific Council also was concerned that the by-catch of small redfish in the new shrimp fishery might significantly impact the redfish resource and recommended a mandatory and immediate use of sorting grates to minimize the by-catch problem. This recommendation was implemented by the Fisheries Commission in 1994 and maximum bar spacing was specified at 28 mm (NAFO, MS 1993). In addition, a minimum mesh size was established at 40 mm; vessels were required to change fishing area immediately by a minimum of 5 naut. miles if by-catches of all regulated groundfish species in any



haul exceeded 10% by weight; and observer coverage was required for a minimum of 10% of a Contracting Party's total estimated fishing days on ground for shrimp. Contracting Parties were further instructed to ensure that their vessels not conduct a directed fishery for shrimp in Div. 3LNO in 1994.

Scientific Council conducted its second assessment of shrimp in Div. 3M in September, 1994, but there was still no basis for the calculation of a TAC. Lower catch rates and smaller shrimp encountered over an expanded fishing area in 1994 were considered reflective of intensive fishing and the Council agreed that a reduction in effort would be required to protect younger animals at lower stock size (NAFO, 1995b). However, no regulations to effectively reduce exploitation were introduced for 1995. By-catch of small redfish in the fishery continued to be a problem because grates with 28 mm bar spacings did not eliminate by-catch of redfish less than 21 cm (NAFO, 1995b). The Fisheries Commission revised the Conservation and Enforcement Measures from the previous year, reducing maximum bar spacing to 22 mm and the by-catch limit for all regulated groundfish species to 5% (NAFO, MS 1994b).

By September, 1995, data on distribution of fishing effort and size composition of the catches showed clearly that the fishing pattern had changed between years. The fishing grounds were expanded over a broader range of depths and effort was being redirected toward small, male shrimp as young as age 2 (about 15 mm carapace length (CL)). Scientific Council could find no practical way to protect the younger animals in the short term other than to close the fishery in 1996. This recommendation was not accepted and, instead, Fisheries Commission implemented effort control. Each Contracting Party was instructed to limit the number of vessels in 1996 to the number that participated in the fishery from 1 January 1993 to 31 August 1995 and to limit the number of fishing days to the maximum number of fishing days observed for their vessels in one of the years 1993, 1994 or up to 31 August 1995 (NAFO, MS 1995). Further, Contracting Parties with no previous record of fishing shrimp in Div. 3M were permitted 100 fishing days by one vessel in 1996 and those with a small track record were permitted an equal number of days. Other management measures from 1994 were reiterated for the 1996 fishery.

### **Catch, Effort and Catch-Per-Unit-Effort (CPUE)**

Catches and sizes of shrimp in spring, 1993, were acceptable by industry standards despite some initial problems with animals having soft shells and pale colour. By late-July, about 50 vessels from up to nine nations were reported fishing for shrimp in the area. The number of vessels decreased over the remainder of the year and only 4 were reported fishing shrimp at the end of December (Parsons, MS 1994). The nominal catch of shrimp from Div. 3M in 1993 was estimated at approximately 28 000 tons.

Fishing continued into 1994 at low intensity. The number of vessels increased from 4 during the first week of January to 17 by late-February and remained near that level until early-April, decreasing shortly thereafter. From mid-April to mid-June, the number of vessels increased from 7 to 47 and then decreased steadily to 3 at the end of the year (Parsons, MS 1995). The catch in 1994 was estimated at just over 24 000 tons.

In 1995, activity was low throughout the January–March period (3 to 8 vessels) but increased substantially from 7 vessels in early-April to 71 by late-July. The number declined steadily over the remainder of the year to 6 during the last week of December (Parsons, MS 1996). The estimated 1995 catch was approximately 33 000 tons.

At least 13 nations participated from the start of the fishery in spring of 1993 to the end of 1995. Largest catches were taken by Norway, the Faroe Islands and Iceland (Table 1).

Fishing effort has been distributed around the bank, concentrated near the 400 m contour. Figure 6 illustrates the area fished for shrimp on the Flemish Cap based on set by set observations from the Canadian (1993–95) and Norwegian (1995) fleets. It is assumed that the fishing activity of Canadian and Norwegian vessels was representative of the total fleet. The fishing grounds for observed activity covered a total of 23 500 km<sup>2</sup> on the east, west and northern portions of the bank at depths between 151 and 620 m. Ninety percent of the activity occurred over about 11 000 km<sup>2</sup> between 275 and 475 m. Areas fished differed among years, covering 11 600 km<sup>2</sup> and a narrow depth range (300–500 m) in 1993 and 12 600 km<sup>2</sup> in 1994. There was little fishing activity on the eastern slope in 1994 and an

TABLE 1. Estimates of catches (tons) of northern shrimp, *Pandalus borealis*, by year and country – 1993 to 1995.

Nation	1993	1994	1995
Canada	3 724	1 041	970
Denmark	800	400	200
Portugal	0	0	150
Spain	240	300	158
Estonia	0	1 081	2 092
Faroe Islands	8 545	6 567	5 987
Greenland	3 788	2 276	2 403
Honduras	1 265	0	0
Iceland	2 243	2 300	7 623
Latvia	0	300	350
Lithuania	0	1 225	675
Norway	7 183	8 460	9 534
Russia	300	300	2 838
St. Vincent	0	75	0
Total	28 088	24 325	32 980

expansion of the grounds to the southwest, compared to 1993. In 1995, the grounds covered a considerably larger area (18 700 km<sup>2</sup>) with a greater range of depths fished (200–500 m) and further expansion in the southwest. Fishing in deeper water (> 600 m) has been reported occasionally in the southwest (Flemish Pass), at times extending into Div. 3L.

In 1993 annual catch rates calculated from vessel logbook data for Canada and Greenland (about 400 kg/hr) were higher than those reported for Iceland and Norway (about 300 kg/hr). Canadian surveillance reports indicated that Russian catch rates were very low compared to all other fleets. Catch rates declined over at least part of the season for several fleets. Canadian monthly averages showed a large decline from May to July, Greenland from May to September, Iceland from June to October and Norway from May to November (Parsons, MS 1994).

In 1994, Canada, Greenland, Iceland and Norway experienced similar mean catch rates, ranging from about 220 to 260 kg/hr. Those for Estonia and Latvia were considerably lower (about 140 kg/hr). Seasonal trends in catch rates also occurred in 1994. Estonian and Norwegian vessels, which fished throughout the year, produced variable or increasing catch rates up to May, followed by an overall decrease to the end of the year. Canadian and Latvian CPUE estimates for the February–June period increased while those for Greenland decreased

from May to September. Icelandic rates were generally variable without trend up to August but declined thereafter (Parsons, MS 1995).

In 1995, the Canadian catch rate (272 kg/hr) was slightly higher than the 1994 value but lower than the 1993 estimate. Monthly CPUE increased from March to May and then declined from May to July. Estonian catch rates in February and March (160–170 kg/hr) were higher than those for the same months in 1994 but, for the April–July period, the 1995 values were lower. A slight decrease occurred from May to August. The Greenlandic annual rate for 1995, when adjusted for double trawls (289 kg/hr), was higher than the 1994 value but lower than in 1993. Monthly CPUE increased during the May–July period. Icelandic monthly rates were variable in 1995 (130–280 kg/hr) and generally lower than those of the previous two years in months where comparisons were possible (Parsons, MS 1996).

Overall, the catch rate data showed considerable variation by fleet, season and year. Vessels from Canada and Nordic nations consistently achieved higher catch rates than those of Baltic vessels. Within fleets, CPUE increased to about May but declined, thereafter, to the end of the year. The 1995 annual CPUE's for most fleets were about the same or slightly higher than the 1994 values, but remained substantially lower than those of 1993. Such sources of variation must be taken into account when interpreting catch rate data as indices of abundance, especially given the expansion of the

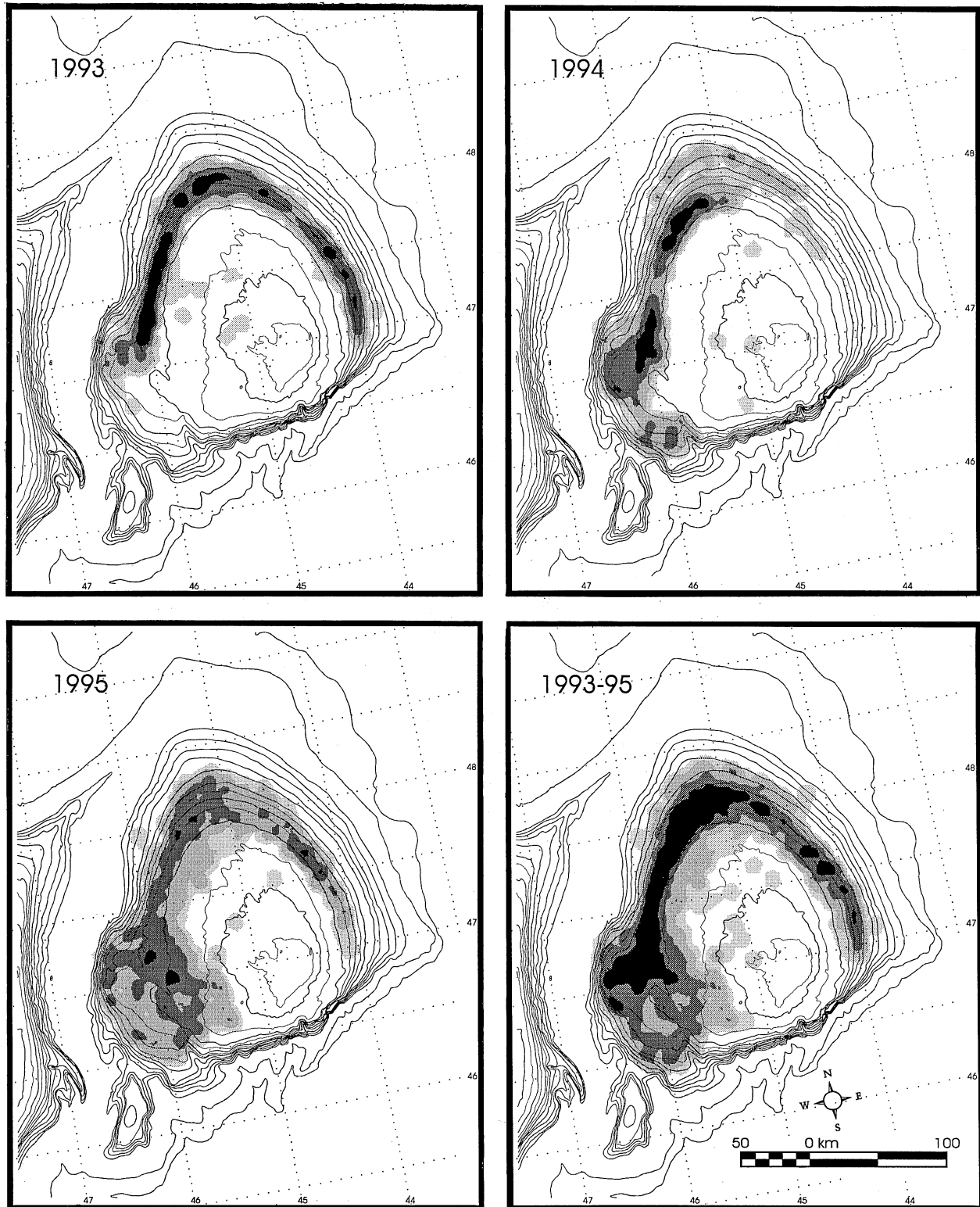


Fig. 6. Fishing grounds for northern shrimp in NAFO Div. 3M, 1993-95. Black areas denote highest concentration of fishing effort. Increasingly lighter shades indicate decreasing effort density. Depth contours are 50 m intervals (light lines are 150, 250, 350 and 450) up to 450 m then at 100 m intervals to 1 000 m, plus 2 000 and 3 000 m.

fishing area into shallower depths over the brief, three-year period.

### By-catch

The small-meshed otter trawl used to catch shrimp frequently results in the incidental capture of fish and other invertebrate species. In Div. 3M, reports of high by-catches from the new shrimp fishery raised concerns in NAFO about the potential damage to groundfish stocks, particularly redfish. In 1994, the Fishery Commission requested information on the potential loss of yield for redfish due to by-catch mortality and the Scientific Council calculated yield losses based on a previous yield-per-recruit analysis for the Div. 3LN stock (NAFO, 1995b). More than 30 000 tons lost yield were projected at both  $F_{0.1}$  and  $F_{max}$ , assuming a shrimp catch of 30 000 tons and a redfish by-catch of 20%. The Council stated that all losses would be spread out over about 15 years but would, in an equilibrium situation, represent annual losses. Losses greater than 20 000 tons would only be realized for strong redfish year-classes.

Fishery observers were deployed on all Canadian vessels during 1993–95 and some Norwegian vessels in 1995. However, the percentage of activity observed for all countries combined was only 8% in 1993, 4% in 1994 and 5% in 1995. Observers recorded details of the catches on a set-by-set basis and this information was used to examine catch and discarding of by-catch.

The weight of each species taken in each set was estimated by sampling the total catch according to methods outlined in Kulka (MS 1996) and Kulka and Firth (MS 1987). Maps of fishing grounds were produced by converting point data (in this case, set-by-set fishing locations) to effort density surfaces using potential mapping of SPANS, similar to the methods of Kulka *et al.* (1995) and Kulka and Power (MS 1996). Similarly, potential maps of shrimp and redfish were produced from set-by-set estimates of catch per hour to illustrate distribution of the two species on the fishing grounds.

Table 2 lists the estimated total catch by species from the observed shrimp fishery adjusted to the total shrimp catches of all countries for each year, assuming proportions of by-catch were similar among fleets. The quantity of by-catch, as a percentage of total catch, declined from 33.3% in 1993 to 21.9% in 1994 and to 2.6% in 1995. Of the com-

mercially important species, redfish (*Sebastes* sp.) was found to dominate the by-catch. No other species accounted for more than 1% of the catch in any year. The percentage of the total redfish catch declined from 28.4% in 1993 to 19% in 1994 and 1.1% in 1995. In 1995, with use of 19–22 mm grates, the dominant by-catches were small or thin fish, such as young redfish, lanternfish and eelpout that are of similar width to shrimp.

Significant changes occurred in the configuration of the fishing gear among years related to the mandatory use of sorting grates in 1994 and changes in bar spacings in the grates between 1994 and 1995. In 1994, 75% of the sets observed had 28 mm spacing while 10%, 10% and 5% were 27, 26 and 25 mm, respectively. In 1995, 61%, 7% and 31% of sets had 22, 20 and 19 mm spacing. In 1994, the percent of redfish by-catch increased with decreasing grid size between 28 and 26 mm but was lowest at 25 mm. In 1995, redfish by-catch was less than 3%, regardless of grate size used (Fig. 7). The greatest differences were among years rather than among grate space categories within years.

Some differences were observed between the distribution of shrimp (Fig. 8) and redfish (Fig. 9). In 1993, high by-catches of redfish (>50 kg per hr) were distributed over 83% (9 600 km<sup>2</sup>) of the total grounds including all of the west and northwest areas. The densest shrimp concentrations (>500 kg per hr) were located over a less extensive area (3 500 km<sup>2</sup>) of the western and northern parts of the Flemish Cap. An overlay of shrimp and redfish catch distributions (Fig. 10) shows two patches of high shrimp catch with low redfish by-catch in 1993. Areas of high by-catch and low shrimp catch tended to be found on the periphery of the grounds. For 1994, high shrimp catches were attained in only 2% of the area while high by-catches of redfish covered 33% of the grounds. High shrimp/low by-catch areas were more patchy than in 1993 and were located on the inner portion of the northern area and on the southern extension of the grounds. In 1995, the high shrimp/low by-catch areas were located mainly to the shallower northwest and southwest areas not previously fished. Redfish catch rates within the shrimp fishing grounds did not show any trend with depth.

Measurements of redfish taken in shrimp trawls during May, 1993 showed a single mode of small fish at 14 cm (Parsons *et al.*, MS 1993). This size

TABLE 2. Estimates of total catches (tons) by species from the observed shrimp fishery on Flemish Cap adjusted to the total estimated shrimp catches of all countries for the years 1993, 1994 and 1995.

Species Common name	1993		1994		1995		Average	
	Catch	Percent	Catch	Percent	Catch	Percent	Catch	Percent
Shrimp	28 088.0	66.74	24 325.0	78.15	32 980.0	97.41	28 464.3	80.8
Redfish	11 970.0	28.44	5 902.7	18.96	374.2	1.11	6 082.3	16.2
Greenland halibut	309.2	0.73	96.7	0.31	32.2	0.10	146.0	0.4
Spotted wolffish	392.5	0.93	20.3	0.07	12.5	0.04	141.8	0.3
Skates	354.2	0.84	22.8	0.07	12.2	0.04	129.7	0.3
Striped wolffish	176.8	0.42	69.0	0.22	56.4	0.17	100.7	0.3
Lanternfish	70.2	0.17	63.6	0.20	144.7	0.43	92.8	0.3
Eelpout	38.5	0.09	82.4	0.26	75.8	0.22	65.6	0.2
Common grenadier	5.5	0.01	79.7	0.26	27.3	0.08	37.5	0.1
Roughhead grenadier	15.8	0.04	75.9	0.24	7.8	0.02	33.2	0.1
Greenland shark	46.6	0.11	50.1	0.16	0.0	0.00	32.2	0.1
Capelin	65.5	0.16	12.8	0.04	2.7	0.01	27.0	0.1
Plaice	59.9	0.14	11.1	0.04	6.4	0.02	25.8	0.1
Northern wolffish	69.7	0.17	0.2	0.00	0.0	0.00	23.3	0.1
Witch flounder	31.9	0.08	12.1	0.04	5.3	0.02	16.4	0.0
Longfish hake	14.1	0.03	24.6	0.08	5.8	0.02	14.8	0.0
Viperfish	10.1	0.02	19.6	0.06	5.7	0.02	11.8	0.0
Basking shark	35.3	0.08	0.0	0.00	0.0	0.00	11.8	0.0
Lancetfish	24.5	0.06	3.0	0.01	6.1	0.02	11.2	0.0
Snipe eel	10.4	0.02	15.9	0.05	2.1	0.01	9.5	0.0
Barracudina	4.0	0.01	15.9	0.05	7.3	0.02	9.1	0.0
Cod	18.9	0.04	2.3	0.01	0.3	0.00	7.2	0.0
Roundnose grenadier	10.4	0.02	10.3	0.03	0.1	0.00	6.9	0.0
Silver hake	0.1	0.00	17.4	0.06	0.0	0.00	5.8	0.0
Halibut	8.0	0.02	0.0	0.00	0.0	0.00	2.7	0.0
Other	255.6	0.61	192.4	0.62	92.1	0.27	180.0	0.5
Total	42 085.9		31 125.8		33 856.8		35 689.5	

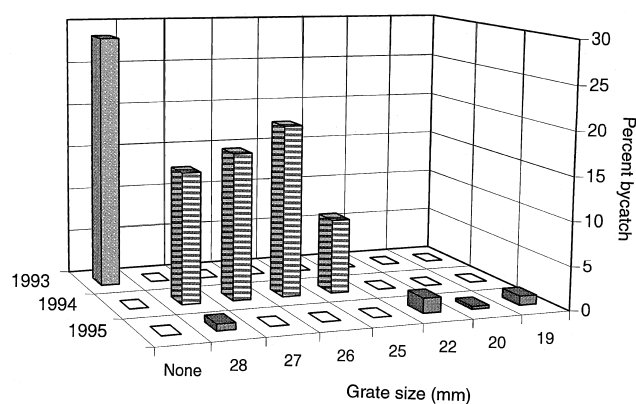


Fig. 7. Percent of redfish in the NAFO Div. 3M shrimp fishery by grate size and year.

group, possibly representing one or two year-classes produced in the late-1980s (Saborido-Rey, MS 1995), also was evident in June and July but was

accompanied by larger/older fish forming modes at 23 cm in June and 19 cm in July. Redfish caught from April to June, 1994, despite the mandatory sorting grate (28 mm bar spacings), were unimodal at 17–18 cm and were presumed to belong, primarily, to the same late-1980s year-class or year-classes discussed above. In 1995, bar spacings were reduced to 22 mm or less and redfish by-catch was very low compared to the previous two years (Parsons and Veitch, MS 1995; Siegstad and Hvingel, MS 1995).

Length samples of redfish collected by observers in 1993, 1994 and 1995 were used to estimate the numbers discarded from the shrimp fishery each year (Fig. 11). In 1993, an estimated 227.6 million redfish with modal length of 14 cm were caught as by-catch and discarded. Estimates of 89.1 million and 4.8 million redfish with average length of about 18 cm were taken in 1994 and 1995, respectively.

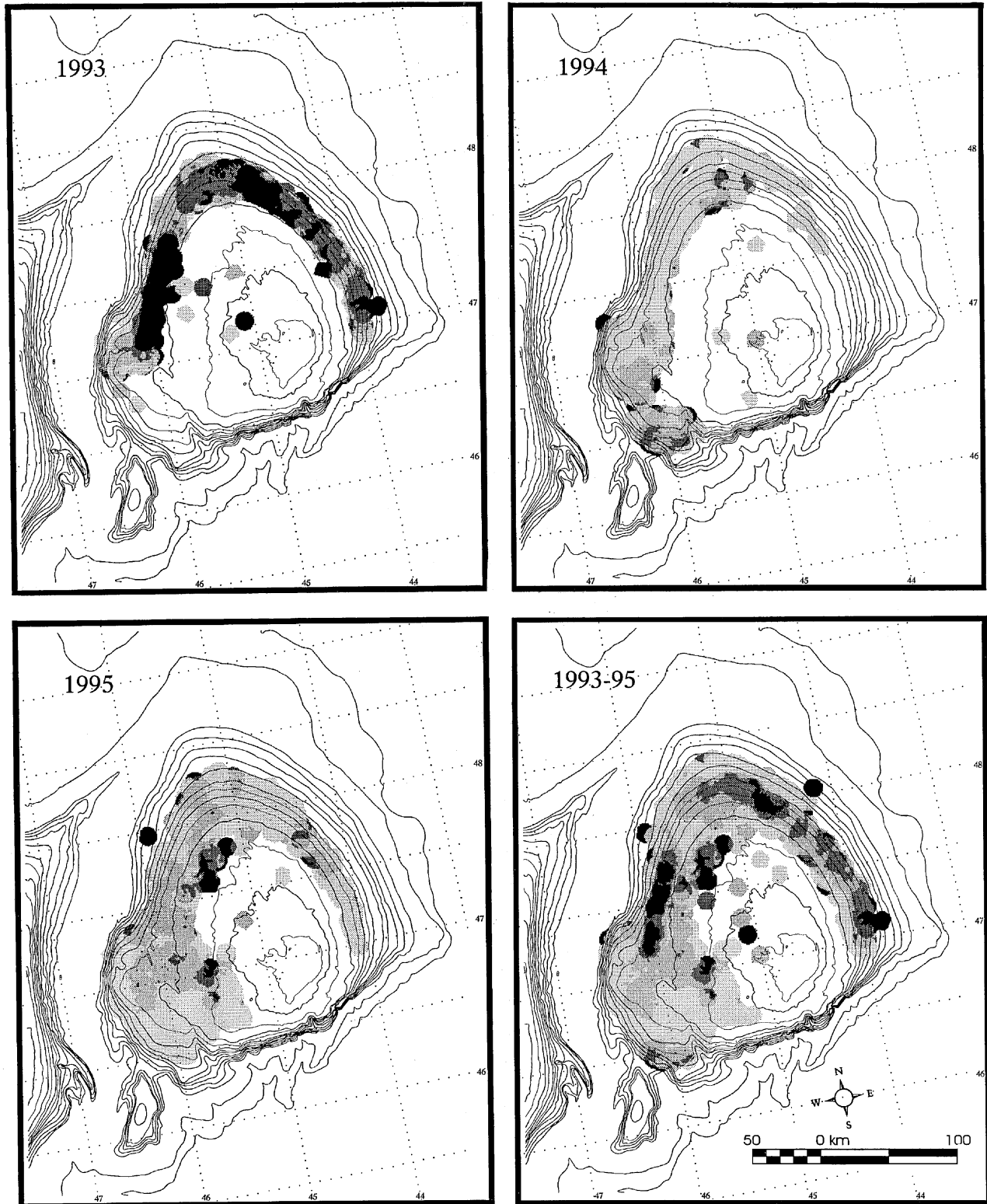


Fig. 8. Density of shrimp in NAFO Div. 3M, 1993-95. Black areas denote areas where kg per hr in the fishery exceeded 500, dark grey, 400-500, medium grey, 300-400 and light grey less than 300. Depth contours are 50 m intervals (light lines are 150, 250, 350 and 450) out to 450 m then at 100 m intervals to 1 000 m, plus 2 000 and 3 000 m.

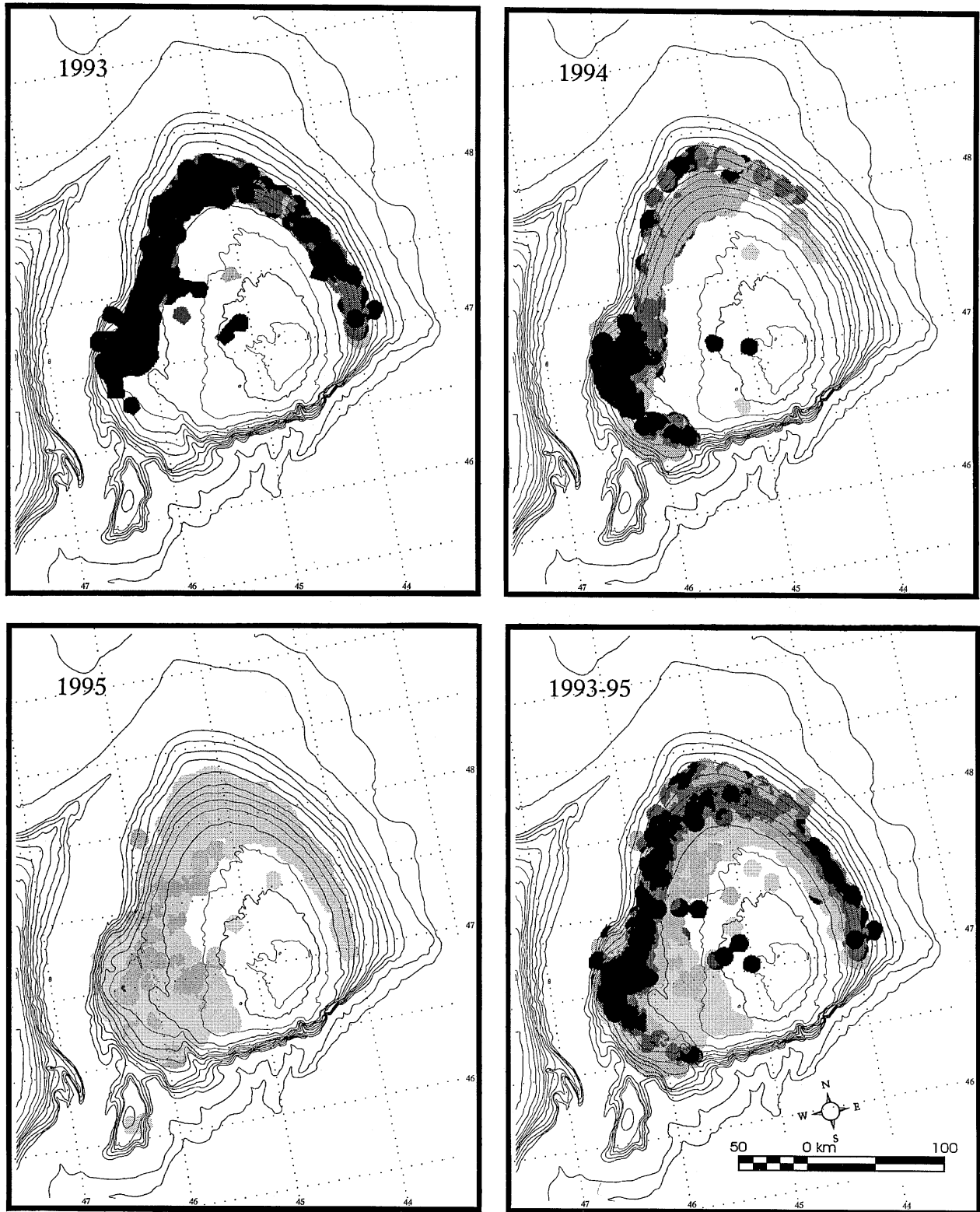


Fig. 9. Density of redfish in the northern shrimp fishery in NAFO Div. 3M, 1993–95. Black areas denote areas where kg per hr exceeded 50, dark grey, 30–50, medium grey, 7–30 and light grey less than 7. Depth contours are 50 m intervals (light lines are 150, 250, 350 and 450) out to 450 m then at 100 m intervals to 1 000 m, plus 2 000 and 3 000 m.

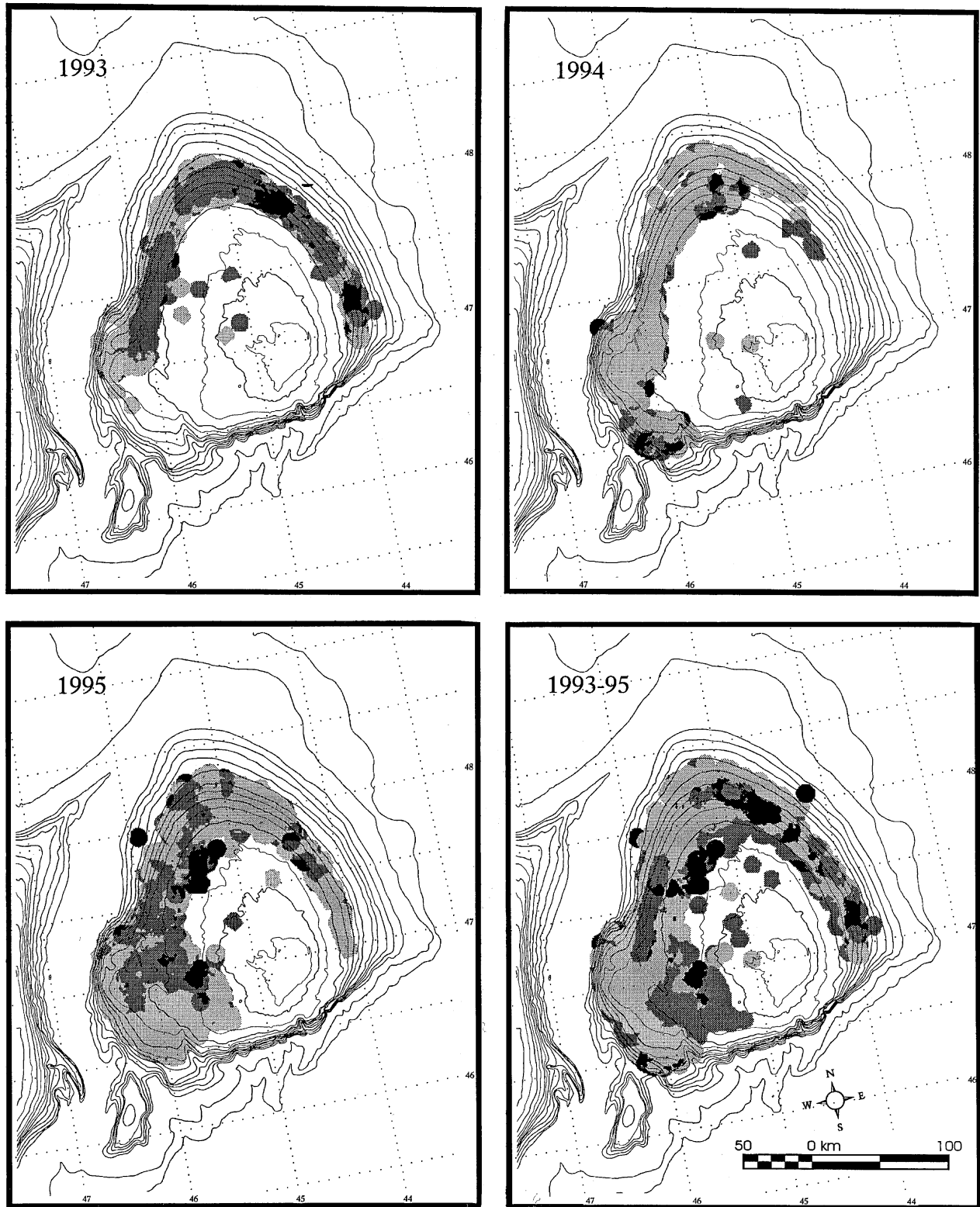


Fig. 10. Overlay of shrimp and redfish. Black indicates high shrimp catch/low redfish by-catch and light grey indicates low shrimp catch/high redfish by-catch.



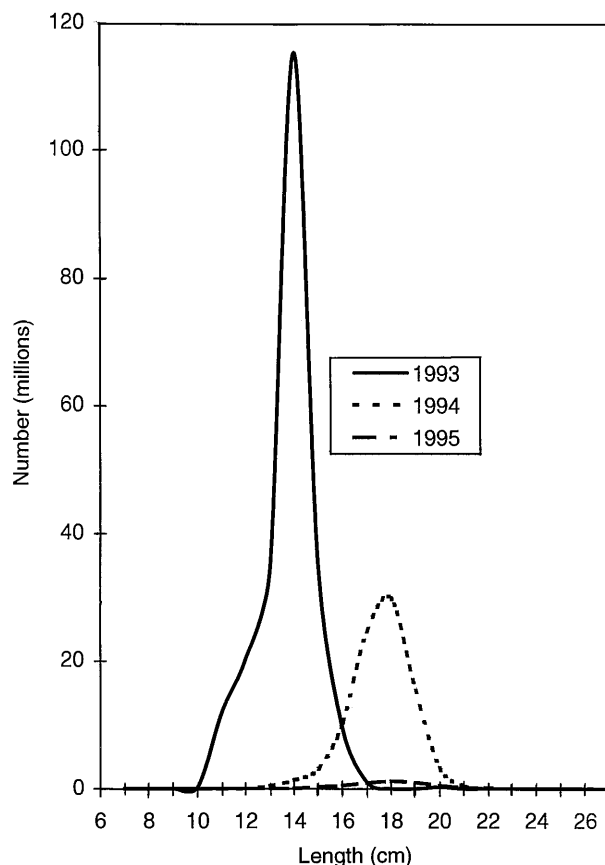


Fig. 11. Numbers at length for redfish taken as by-catch from the 1993, 1994 and 1995 shrimp fisheries in NAFO Div. 3M.

## Biology of *P. borealis* on Flemish Cap

### Distribution

Research bottom-trawl surveys on Flemish Cap by EU–Spain have been conducted since 1988 (Vazquez, MS 1989; Sainza, MS 1995) using a standardized survey method. These surveys were designed for demersal fish but also provided information on distribution and relative abundance of shrimp because a codend liner with 35 mm mesh was used.

Survey results show that shrimp are found around the bank with highest densities in the western, northern and northeastern areas at depths between approximately 250 and 550 m (Escalante *et al.*, MS 1990; Mena, MS 1991, MS 1992; Sainza, MS 1993a,b, MS 1994, MS 1995). Slopes in the south and southeast appear to be sparsely populated (Fig. 12). The surveys also provided length distributions for each stratum fished which showed that

smaller, male shrimp were more prevalent in depths less than 400 m, a mixture of sizes and sexes occurred between 400 and 500 m and the larger, female shrimp dominated in depths greater than 500 m (Escalante *et al.*, MS 1990; Sainza, MS 1993a, b, MS 1994, MS 1995).

The shrimp fishery on Flemish Cap also provided information on distribution. Areas and depths (250–500 m) which attract the most fishing effort reflect, to some extent, the densest concentrations of marketable shrimp. Little or no fishing occurred in the southern and southeastern areas of the bank (Nicolajsen, MS 1993, MS 1994a, MS 1995; Parsons and Veitch, MS 1994, MS 1995; Parsons *et al.*, MS 1993; Siegstad, MS 1993, MS 1994; Siegstad and Hvingel, MS 1995), consistent with the general scarcity of shrimp seen in the EU–Spain survey data. The fishery in 1995 extended into shallower waters (200–300 m) of the western grounds where small, male shrimp were abundant (NAFO, 1996) (Fig. 6 and 8).

Lilly (MS 1993) calculated partial fullness indices for shrimp found in cod stomachs during 1980–83 on Flemish Cap and showed that shrimp were present in stomachs of cod caught in depths of 250–500 m, consistent with the findings of the EU–Spain research trawl surveys and inferences from the commercial fishery. Occurrence of shrimp was low in cod caught on top of the bank but shrimp distribution at depths beyond 500 m was difficult to infer because cod catches were low at those depths.

### Biomass

Relative biomass estimates for shrimp on Flemish Cap, calculated by areal expansion, are available from trawl surveys conducted since 1988 (Sainza, MS 1995). From 1988 to 1990, biomass appeared to be stable at an index of about 2 000 tons (Table 3). In 1992, the index increased sharply to over 16 000 tons but declined thereafter to 3 300 tons in 1994 and 5 400 tons in 1995. The 1994 estimate was likely biased downward due to a larger-mesh liner in the codend of the trawl that year (NAFO, 1996). Standard errors of the mean catch per mile showed increased variation with the higher estimates. A comparison between the 1995 biomass estimate (5 413 tons) and the provisional catch (about 33 000 tons) illustrates that the research catches provide a relative index and not a measure of absolute biomass.

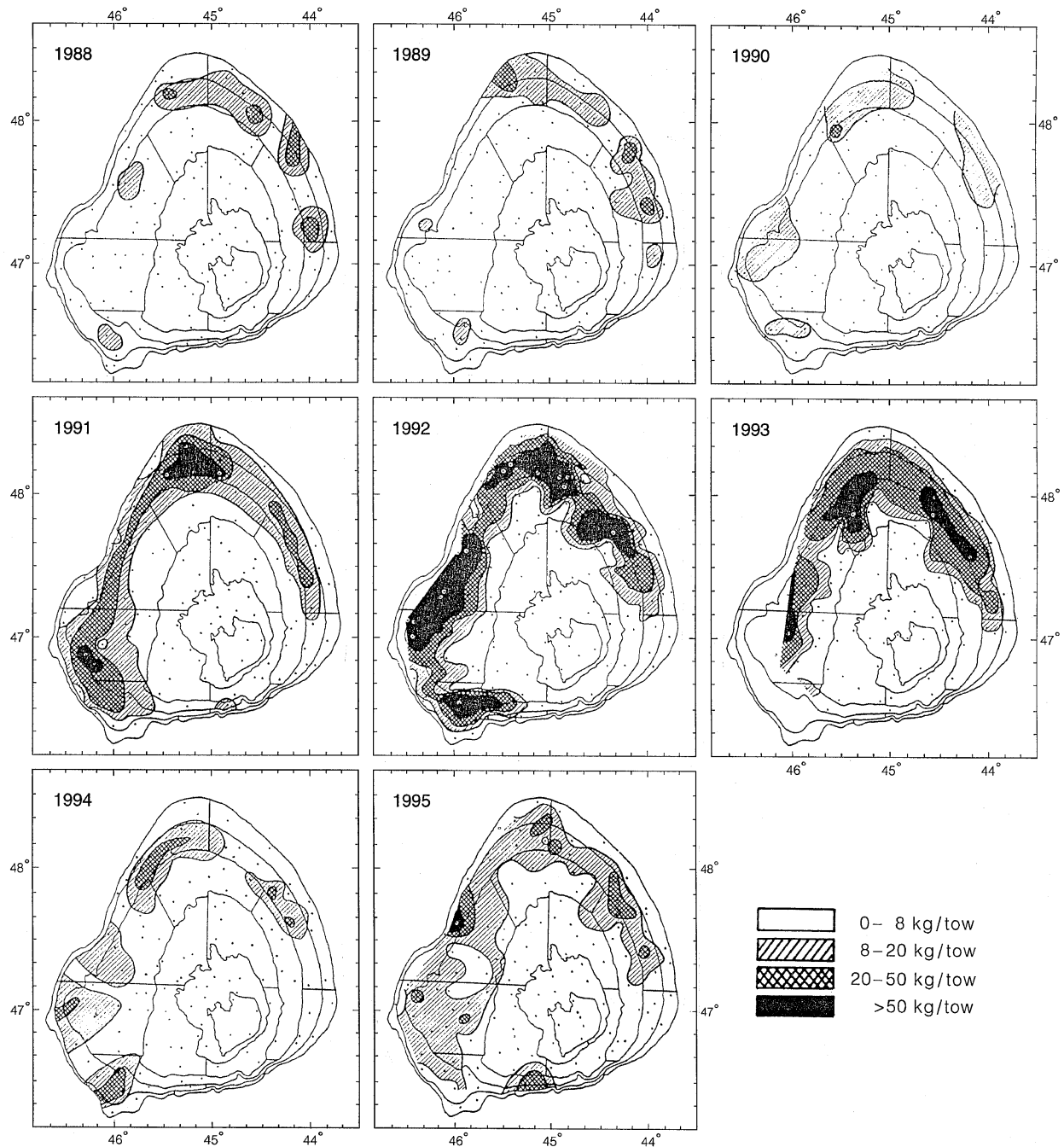


Fig. 12. Shrimp density on Flemish Cap as determined from EU-Spain research trawl surveys, 1988-95. (A. Vazquez, Inst. Inv. Mar., Vigo, Spain, pers. comm.).

Shrimp biomass was concentrated in depths of 250-550 m (Sainza, MS 1995), similar to the depth range of the commercial fishery. Shrimp also were present in two deeper strata (>550 m) on the northern edge of the bank, whereas a shallow stratum (150-180 m) near the centre of the Cap produced

shrimp catches only in 1995. The increase in biomass from 1990 to 1992 occurred across all strata in which shrimp were found during the initial surveys. In 1994 and 1995, a greater proportion of the estimated biomass was located in western and southwestern areas, compared to previous

TABLE 3. Biomass indices for northern shrimp, *Pandalus borealis*, estimated from EU–Spain research surveys on Flemish Cap, 1988–95.

Year	Biomass index (tons)	Mean catch kg/mile	Standard error kg/mile
1988	2 164	1.54	± 0.28
1989	1 923	1.37	± 0.24
1990	2 139	1.53	± 0.21
1991	8 211	5.83	± 0.71
1992	16 531	11.75	± 1.86
1993	9 256	6.57	± 1.04
1994	3 337	2.37	± 0.35
1995	5 413	3.85	± 0.44

years, while shrimp densities in the eastern areas declined substantially, consistent with the westward shift in fishing effort.

Nicolajsen (MS 1995) used commercial fishery data to estimate biomass in 1993 and 1994. Average shrimp density (catch/area swept) within each square of 10° longitude by 7.5° latitude was calculated and multiplied by the area of the square. Estimates of biomass summed over all squares decreased from about 24 000 tons in 1993 to 14 600 tons in 1994.

### Length, Sex and Maturity

Size and sex of shrimp on Flemish Cap have been recorded from the EU–Spain research surveys, beginning in the late-1980s, and from the commercial fishery, beginning in 1993. The standard measurement taken in most cases was the oblique carapace length (CL), measured from the posterior margin of the orbit to the posterodorsal margin of the carapace (Rasmussen, 1953). Sex and maturity (males, transitionals, primiparous and multiparous females) were determined from pleopod characteristics (Rasmussen, 1953) and condition of sternal spines (McCrary, 1971).

Relative abundance-at-length was estimated from research surveys conducted during 1990 to 1995 (Sainza, MS 1995). These data (Fig. 13) traced a prominent size-group of males starting in 1990 which appeared to change sex over a three year period. This component was evident in the population as entirely females in 1994. Other components were traced in subsequent years but showed sex change over one or two years and lower abundance.

Samples from the commercial fishery showed major changes between years in the sizes of shrimp caught. In 1993, catches were composed primarily of large female shrimp whereas, in 1994 and 1995, males became more important (NAFO, 1996). By 1995, most of the catch in numbers was due to the smallest size group of males (Parsons and Veitch, MS 1995; Siegstad and Hvingel, MS 1995).

Weight ( $W$  in g) carapace-length ( $L$  in mm) relationships of the form  $W = aL^b$  were first derived by Escalante *et al.* (MS 1990) and Mena (MS 1991) from EU–Spain survey samples using lateral carapace length, measured from the posterior margin of the orbit to the posterolateral margin of the carapace. They calculated relationships separately for males, primiparous females, multiparous females, total females and total for 1988, 1989 and 1990. Coefficients ( $a$ ) ranged from 0.00032 to 0.00100 and exponents ( $b$ ) from 2.72 to 3.07. Nicolajsen (MS 1994b) pooled animals of 16 to 29 mm oblique CL taken from Flemish Cap and the adjacent area in Div. 3L from September 1993 to March 1994, and derived the relationship:  $W = 0.0004L^{3.1474}$ . Skuladottir (MS 1994) used data from the Icelandic fishery on Flemish Cap in 1994 to produce the relationships:  $W = 0.000596L^{3.017}$  for animals without eggs and  $W = 0.000693L^{2.99}$  for egg-bearing females (Fig. 14).

### Age and Growth

The first interpretation of age structure from EU–Spain survey results identified three size groups with modes around 18, 22 and 25 mm as ages 1, 2 (males) and 3 (females) (Mena, MS 1991). Parsons and Veitch (MS 1993) reanalysed the

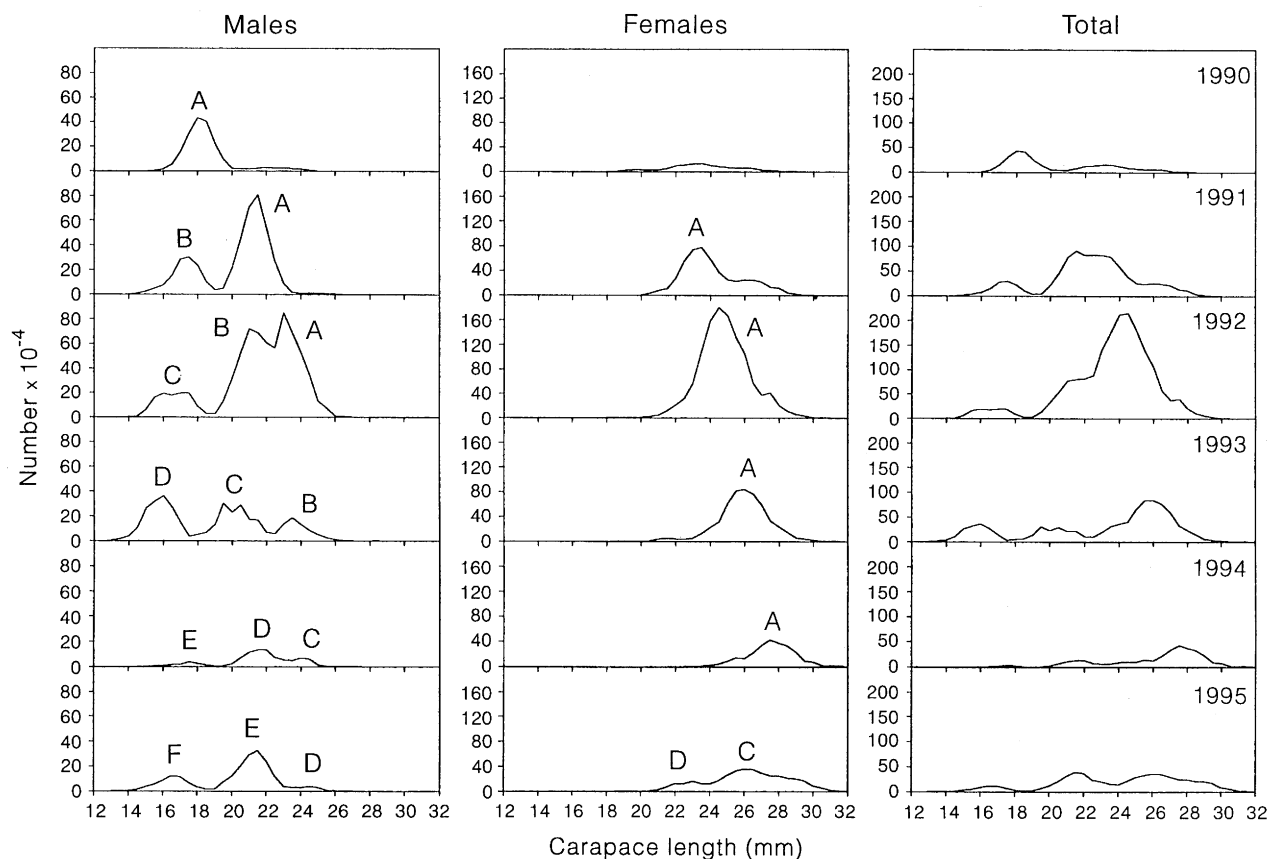


Fig. 13. Time series of research survey length frequency distributions of shrimp on Flemish Cap, 1990–95. A to D denote presumed year-classes (from Sainza, MS 1995).

1988–92 survey data, converting lateral carapace length to oblique carapace length when necessary. They found a size group of males between 16 and 19 mm carapace length (mode about 18 mm) each year with additional male components at approximately 20–21 mm and 23 mm. Females usually occurred at a mode of 25–26 mm. Size compositions from the 1993 fishery by Canadian vessels were consistent with survey data, but size-specific sex compositions were inconsistent in some years.

Shrimp found in cod stomachs taken from the area during the winters of 1978–84 showed a distinct size group at 7 mm, as well as larger sizes (Lilly, MS 1993). Parsons and Veitch (MS 1993) interpreted these 7 mm shrimp as males hatched in spring of the previous year. Hence, the first male size group evident in trawl samples (16–19 mm) was thought to be age 2 and the male components at 20 and 23 mm ages 3 and 4, respectively. They further concluded that, if sex inversion occurred at a specific age, primiparous females would be age 5 and

multiparous females ages 6+. However, commercial and research survey time series showed variation in the timing of sex change. The data sources further revealed that a strong year-class was produced in the late-1980s, possibly the 1988 year-class.

Skuladottir and Einarsson (MS 1993) analyzed Icelandic commercial samples from 1993 and found three male cohorts (ages 2, 3 and 4) and three female cohorts (ages 5, 6 and 7). They also analyzed the 1992 EU–Spain survey data which indicated that some of the age 4 animals had already changed sex. Generally, their findings were similar to those of Parsons and Veitch (MS 1993). Skuladottir (MS 1994) also identified the 1988 year-class as strong, and compared length-at-age between samples taken in 1993 and 1994. Nicolajsen (MS 1994c) estimated age composition of shrimp from Faroese catches in 1993 and found that the age 5 group (the 1988 year-class) was dominant, that females appear as early as age 3 and that all animals are female by age 5.

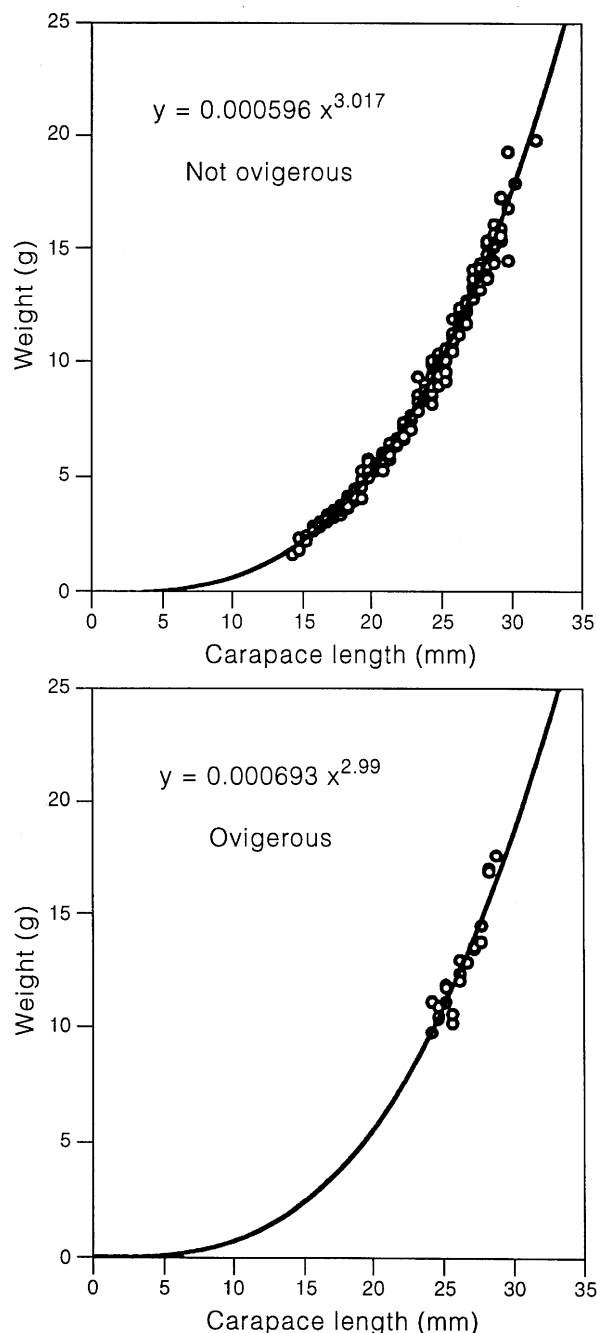


Fig. 14. Weight-length relationships for shrimp caught on Flemish Cap by the Icelandic fishery in 1994 (from Skuladottir, MS 1994).

By 1995, there was general agreement amongst investigators that three modes of male shrimp, representing ages 2, 3 and 4, usually occur in catches from both the survey and the commercial fishery. There was also a component of females which were assumed to be primarily age 5+ and can be broken

down to age 5 and 6+ on the basis of the sternal spine characteristics (McCrary, 1971). The ageing is complicated, however, as it has been inferred that some animals in some years change sex between ages 2 and 3 (Sainza, MS 1994) and between ages 3 and 4 (Skuladottir and Einarsson, MS 1993; Nicolajsen, MS 1994c; Parsons and Veitch, MS 1995).

### Reproduction

The fishery for shrimp on Flemish Cap is not restricted by season, catch limit or natural closures due to ice cover, unlike several other fisheries. Thus, the area has produced samples of shrimp which cover the complete reproductive cycle. The proportion of ovigerous females increased during the EU-Spain research survey in the summer of 1990, suggesting that spawning (egg deposition) occurs around late-July to early-August (Mena, MS 1991). Commercial fishery data from Icelandic vessels in 1994 indicated that spawning occurred mainly in August and that all females seemed to spawn each year (Skuladottir, MS 1994). The incidence of ovigerous females in samples taken on Faroese vessels decreased from March through May (Nicolajsen, MS 1994b), indicating that hatching was occurring. Thus, the ovigerous period (egg incubation time) is about 9 months (August to April, inclusive).

Fecundity was estimated from female shrimp taken during the 1990 research survey (Mena, MS 1991). The relationship was  $F = 1.902 CL^{2.017}$  where  $F$  is the number of eggs and  $CL$  is the oblique carapace length in mm.

### Community Structure

The Flemish Cap has been the subject of intensive environmental research on both physical and biological processes since the mid-1970s (see overview by Lilly, 1987). The area traditionally has supported a commercial fishery dominated by Atlantic cod (*Gadus morhua*) and redfish (*Sebastes* sp.) (Templeman, 1976). Capelin (*Mallotus villosus*) and sand lance (*Ammodytes dubius*), the dominant shelf-dwelling pelagic fish on the adjacent Grand Bank, are generally thought to be rare visitors (Lilly, 1987). However, Frank *et al.* (1996) observed that capelin occurred in abundance during several years in the early-1990s. Table 2 lists several of the species and species groups encountered in the fishery as by-catch.

Wells and Baird (MS 1989) listed 75 fish species from the Flemish Cap over a depth range of 130-730 meters, noting 21 as predominant. Skates (*Raja* sp.), wolffish (*Anarhichas* sp.), redfish (*Sebastes* sp.), Atlantic cod, American plaice and witch flounder were common throughout the depth range, while Greenland halibut, longfin hake, grenadiers (Macrouridae), lanternfish (Myctophidae) and eelpouts (*Lycodes* sp.) occurred primarily in depths greater than 260 m. Paz and Casas (MS 1995) analyzed data from bottom trawl surveys (1989-94) to define zonation and associations of fish fauna on the Cap. They defined three depth zones: <300 m where Atlantic cod and redfish (*Sebastes marinus*) dominated the biomass; 301-600 m dominated by redfish (*Sebastes mentella*); and >600 m where Greenland halibut comprised most of the biomass but where *S. mentella* and species of grenadier were also abundant. Vazquez (MS 1995), analyzing the same data set as Paz and Casas (MS 1995) for biomass and abundance of various groundfish species of commercial interest, also produced biomass estimates for squid (*Illex* sp.) and northern shrimp. It appears, however, that most of the work on community structure and faunal assemblages in the Flemish Cap area has focused on demersal fish species.

### Predators

Northern shrimp are preyed upon by many of the demersal fish which are reported in bottom-trawl catches on Flemish Cap. Rodriguez-Marin *et al.* (MS 1994) surveyed the feeding habits of 14 species of fish in summer 1993 and constructed an index of relative importance for prey species using data on frequency of occurrence and percentages of prey by number and weight. They found northern shrimp to be of high importance for thorny skate (*Raja radiata*); of moderate importance for longfin hake (*Urophycis chesteri*), Greenland halibut (*Reinhardtius hippoglossoides*), roughhead grenadier (*Macrourus berglax*), and spotted wolffish (*Anarhichas minor*); and of low importance for beaked redfish (*S. mentella*), cod (*G. morhua*), Atlantic wolffish (*Anarhichas lupus*) and Arctic eelpout (*Lycodes reticulatus*). Northern shrimp were either absent from or occurred rarely in the stomachs of other redfish (*S. marinus* and *S. fasciatus*), common grenadier (*Nezumia bairdi*), American plaice (*Hippoglossoides platessoides*) and witch flounder (*Glyptocephalus cynoglossus*). Other studies agree that northern shrimp are of low importance for redfish (Konstantinov *et al.*, 1985; Paz *et*

*al.*, MS 1989; Albikovskaya and Gerasimova, 1993) and of very low importance for American plaice (Konstantinov *et al.*, 1985; Paz *et al.*, MS 1989).

The majority of feeding studies on the Flemish Cap have focused on cod because of its large individual size, high biomass and importance to the fishery. Northern shrimp were found to be prey of cod during exploratory surveys by the Soviet Union in 1959 and 1960 (Popova, 1962), and continued to be noted as prey in Soviet and Russian studies between 1964 and 1988 (Turuk, 1968; Konstantinov *et al.*, 1985; Albikovskaya and Gerasimova, 1993). Shrimp also were found to be prey for cod in Canadian studies during 1978-84 (Lilly, MS 1993), and in Spanish studies during 1988-93 (Cardenas *et al.*, MS 1993; Paz *et al.*, 1993; Casas and Paz, MS 1994). However, most reports emphasize predation by cod on commercially important fish (e.g. redfish and cod) (Lilly, 1987). In studies that included shrimp, they ranked as the third or fourth most important prey of cod, after hyperiid amphipods, juvenile redfish and sometimes lanternfish (Myctophidae). Studies further revealed that shrimp are eaten by a broad size range of cod (Konstantinov *et al.*, 1985; Lilly, MS 1993) and that predation occurs over much of Flemish Cap, particularly in an arc from the southwest to the north and east (Lilly, MS 1993). Predation on shrimp occurs throughout the year. However, Turuk (1968) stated that the feeding by cod on shrimp is reduced to a minimum during summer and autumn, and Albikovskaya and Gerasimova (1993) reported that predation by redfish on shrimp "increased in autumn and winter when the biomass of other major food items was at a low level".

It is difficult to determine if the intensity of predation by cod on shrimp has varied over time because studies have differed in many ways, including time of year, spatial coverage, sampling protocol, and method of reporting. Lilly (MS 1993) found that the quantity of shrimp in cod stomachs was low in the late-1970s, increased in the early-1980s, and declined by 1984. Changes in the number of shrimp at length in the cod stomachs were consistent with the hypothesis that a pulse of shrimp recruitment occurred in 1979 and 1980. However, the increase in shrimp biomass on Flemish Cap in the early-1990s was not reflected in an increase in the intensity of predation by cod. The partial fullness index of shrimp in cod stomachs and the contribution of shrimp to the cod diet on a percentage weight basis were much lower in 1989-92 (Casas and Paz, MS

1994) than in 1980–83 (Lilly, MS 1993). This may be related to the seasonality of the studies; the observations in 1989–92 were in summer whereas those in 1980–83 were in winter.

### General Discussion

Recent oceanographic, meteorological and ice conditions of the Northwest Atlantic have been dominated by three anomalous periods; the early-1970s, mid-1980s and early-1990s. During these periods, strong positive winter North Atlantic Oscillation (NAO) index anomalies were associated with colder than normal air temperatures over the Northwest Atlantic, increased ice cover and colder and fresher oceanographic conditions over most of the continental shelf in Atlantic Canada. The temperature anomalies on the Flemish Cap show very similar patterns and are highly correlated with severe meteorological and ice conditions experienced over the same time intervals in the Northwest Atlantic. It is not yet clear how the oceanography of the Flemish Cap relates to changes in shrimp abundance and biology. Strong year-classes appear sporadically and their abundance might depend on environmental conditions (e.g. maintenance of the gyre at critical periods) as well as on the abundance of the spawning biomass. Size and age at sex inversion might be related to temperature but are likely to be density dependent, as well. The role of the environment in determining shrimp abundance and affecting life history characteristics requires a substantial research commitment.

It is unknown whether northern shrimp on Flemish Cap constitute a separate population. The anticyclonic gyre provides a mechanism for larval retention similar to that implied for ichthyoplankton. Shrimp larvae are generally believed to remain within the first 50 m of the water column for two or three months. Information on recirculation and resident times suggest that larvae could be retained over the Cap until they reach the juvenile, settling stage. However, larval drift from areas of the northeast Newfoundland and Labrador Shelf and retention on the Cap also are possible. A clearer understanding of recruitment processes is critical for reliable evaluation of stock conditions.

Age and growth of shrimp have been studied extensively and there is consensus among researchers that the 1988 year-class was strong. Age interpretation is complicated, however, as a result of

variation in the age at sex reversal, both within and between cohorts. Generally, the biological characteristics defining growth and maturation of shrimp on Flemish Cap resemble those of warmer water populations during the early life history stages (first year or two) and colder water populations, thereafter. This is consistent with influences of the Gulf Stream during the early stages and the effects of the colder water, at greater depths, during the later stages. Average egg production per female in this area appears to be similar to or slightly lower than that observed in some northern populations (e.g. Teigsmark, 1983; Parsons and Tucker, 1986) but lower than in the Gulf of Maine (Haynes and Wigley, 1969).

The fishery has been intensive but no effective regulations to reduce fishing mortality have been introduced, despite uncertainty in stock status and a need for a cautious approach to exploitation. Assessment tools are limited. Commercial catch rates are difficult to interpret as indices of abundance because the fishery has changed spatially over time in order to maximize catch rates of smaller male shrimp, as female abundance declined. Although the EU–Spain groundfish surveys on Flemish Cap provide a valuable time-series of information on shrimp, directed shrimp surveys also are required to assess the fishable stock and estimate the recruitment.

By-catch in the fishery has been reduced through the mandatory use of sorting grates. These devices are effective at eliminating large fish from the catches but small fish of several species can still be captured by the trawl. Therefore, if strong year-classes of fish are produced from time to time, by-catch will be problematic as long as individuals are small enough to pass through the bar spacings of the grates. It is difficult to assess the efficacy of the sorting grates in reducing the by-catch of small redfish. As sorting devices were introduced and bar spacings were decreased, the fish (possibly representing a strong year-class or two) grew in size and decreased in numbers through mortality.

Predators of shrimp on Flemish Cap are numerous. However, there have been no attempts made at estimating the number or weight of shrimp consumed by predators and the relationship between shrimp abundance and predator abundance has not been determined. In addition, there has been no investigation of the degree to which the feeding on

shrimp by various predators might be influenced by the abundance and availability of other prey such as small redfish and hyperiid amphipods. Lilly (MS 1993) concluded that stomach content data from Atlantic cod might provide circumstantial evidence for annual changes in shrimp abundance, but cautioned that there had been no study conducted on Flemish Cap of the relationship between the quantity of shrimp in cod stomachs and the abundance of shrimp. He offered that the number of shrimp at length in cod stomachs might provide greater insights into changes in shrimp abundance.

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