Northwest Atlantic Fisheries Organization

Serial No. N2689

NAFO SCR Doc. 96/16

SCIENTIFIC COUNCIL MEETING - JUNE 1996

THE EFFECTS OF THE HUDSON STRAIT OUTFLOW ON THE BIOLOGY OF THE LABRADOR SHELF

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ABSTRACT

Information collected on the Labrador Shelf are used to examine an hypothesis proposed by Sutcliffe and coworkers that the nutrient influx from Hudson Strait increases primary production on the northern Shelf and that this supports a "conveyor-belt" food chain as the community is transported southward by the mean circulation. This was proposed to account for the greater abundance of fish on the southern Labrador Shelf. If true, the hypothesis suggests that the relative importance of the larger plankton should increase southward along the Shelf. Our results confirm that high nutrient levels occur on the northern Labrador Shelf in summer, due to continuous advection from Hudson Strait, and that these nutrients enhance local plankton production. However, nutrient, chlorophyll-a, plankton and biomass spectra distributions do not support the idea that a developing food chain is advected southward along the Shelf. High fish production on the southern Labrador Shelf may be more related to local prey production through upwelling processes near Hamilton Bank.

INTRODUCTION

It has long been recognized that the temperature and salinity characteristics of the waters over the Labrador Shelf originate in Hudson Strait (Iselin 1927; Dunbar 1951; Kollmeyer et al. 1967). They are formed from a mixture of cold Baffin Land Current waters flowing southward along the Baffin Island shelf, relatively warm deep waters that are of West Greenland Current origin and low salinity waters flowing eastward from Hudson Bay and Foxe Basin (Smith et al. 1937; Sutcliffe et al. 1983). These water masses converge at the eastern entrance of Hudson Strait where strong tidal currents result in intense vertical mixing (Drinkwater and Jones 1987). The residual current carries this resultant mixture onto the Labrador Shelf. The intense mixing results in a reduced range in temperature, salinity and stratification on the northern Labrador shelf relative to the Baffin Island Shelf north of Hudson Strait (Lazier 1982; Sutcliffe et al. 1983). The mixing also elevates the surface nutrient concentrations within Hudson Strait (Drinkwater and Jones 1987) and subsequently on the northern Labrador Shelf (Kollmeyer et al. 1967; Sutcliffe et al. 1983).

Sutcliffe et al. (1983) noted that fish abundance increased southward along the Labrador Shelf and correlated cod recruitment with annual salinity fluctuations such that good recruitment was associated with high salinity. They proposed two hypotheses to explain these observations. First, that the nutrient enrichment of the surface waters on the northern Labrador Shelf from outflow of mixed waters from Hudson Strait results in increased primary production on the northern Labrador Shelf in summer and autumn. This in turn supports a developing food chain that is advected southward along the Labrador Shelf by the residual currents. As a consequence of this advection, the higher levels of the food chain (i.e. larger zooplankton and fish) would be found progressively southward. Second, they suggested that the year-to-year fluctuations in cod recruitment arose because of variations in the amount of available food brought about by changes in the nutrient supply, which itself was correlated with salinity. They went on to suggest a third hypothesis, that in years of high runoff into Hudson Bay, the resultant low salinity waters and high stratification would reduce mixing at the eastern entrance of the Strait, thereby lowering nutrient levels and salinities on the Labrador Shelf. In support of this hypothesis they noted that the seasonal salinity pattern on the Grand Bank mirrored that of the seasonal runoff pattern into Hudson Bay after accounting for the estimated time to advect the low salinity waters from Hudson Bay to the Grand Banks.

Myers et al. (1990) investigated the seasonal salinity cycle on the Grand Banks in greater detail. They found that the salinity minimum reflected the arrival of ice melt from the Labrador Shelf rather than the runoff from Hudson Bay. Through correlation analysis they also showed that the effect of the peak river discharge from Hudson Bay reaches the Grand Banks the following spring, not in the autumn as supposed by Sutcliffe et al. (1983). This later arrival time for the Grand Bank was further supported by observations from moored instruments that showed the lowest salinities in Hudson Strait occurred in late autumn. These results suggest that runoff into Hudson Bay does not play an import role in regulating nutrient supply to the Labrador Shelf in the productive season of summer and early autumn. However, they did not negate the possibility that nutrients from Hudson Strait may initiate an advective food chain thereby playing an important role in determine recruitment success in cod to the south. Indeed, Myers et al. (1993) found that the salinity-recruitment relationship of Sutcliffe et al. (1983) continued to hold through to the early 1990s.

If the advective food chain hypothesis is correct, the relative importance of the larger-sized pelagic organisms should increase downstream from Hudson Strait, i.e. the slope of the particle-size spectra should become more positive southward along the Shelf. To test this hypothesis we undertook an oceanographic field study in September 1985 that included observations on particle spectra covering size ranges from nanoplankton to small fish over the entire shelf region. This paper presents a description of the physical, chemical and biological properties, including the particle-size spectra, over the Shelf during this cruise.

STUDY AREA

The Labrador Shelf consists of several offshore banks separated by a series of channels and gullies, known as saddles (Fig. 1). In the southern half of the shelf these banks are also separated from the coast by deep (> 500 m) marginal troughs. The largest banks, from north to south, include Saglek, Nain, Makkovik, Harrison and Hamilton (Fig. 1). The tops of these banks typically lie between 100 and 200 m below the sea surface. Cartwright Saddle separates Hamilton from Harrison Bank and Hopedale Saddle separates Makkovik from Nain Bank.

The circulation pattern is dominated by the southward flowing Labrador Current. The main branch is concentrated over the steep continental slope with surface speeds of 0.3-0.4 m/s and an estimated transport of 4 Sv (Lazier and Wright 1993). These waters, at times, intrude onto the shelf through the saddles. The inshore Labrador Current (surface currents 0.15-0.25 m/s; transport of 0.8 Sv) flows along the inner half of the shelf. These two branches of the Labrador Current are separated by generally weak and directionally variable flows over the outer banks (Fissel and Birch 1990). At times, Labrador Sea water may flow over the saddles onto the shelf.

DATA AND METHODS

In September, 1985, an oceanographic field study was carried out to determine the possible influence of the Hudson Strait outflow onto the Labrador Shelf. A total of 52 hydrographic stations were occupied in a series of 10 transects across the shelf (Fig. 2). At each station, temperature and salinity were measured using a Guildline CTD (Conductivity-Temperature-Depth) profiler. Salinity calibration samples were collected at upwards of 3 depths from bottles on a rosette attached to the CTD and temperature calibrations obtained from reversing thermometers at these same depths. Salinities are presented within the paper in practical salinity units (psu). The bottles on the rosette were also used to obtain nutrient, chlorophyll and plankton samples at as many as 10 depths. Nutrients (nitrates, phosphates and silicates) were measured during the cruise using an Auto Analyzer II. Chlorophyll-a samples were filtered through 0.45 um Millipore filters, dissolved in acetone solution, and run through a Turner fluorometer. The abundance of small phytoplankton-sized particles (1-125 μm) were determined with a Coulter counter (50 μm and 280 μm tubes) from water samples obtained with the rossette bottles. At twenty-six of the stations (indicated in Fig. 2), phytoplankton (>25 μm), zooplankton and nekton were collected from vertical net hauls (23, 73, 236 and 456 μm mesh size) and oblique Tucker trawls (1600 μm). Plankton collections were size fractionated on a shaking sieve apparatus (Harding et al., 1995) and frozen to -20°C. The plankton species were later identified and the wet and dry weight determined.

RESULTS

Temperature, Salinity and Stratification

Stratification over the Labrador Shelf generally increased towards the south and inshore (Figs. 3 and 4). The most homogeneous station (54) was adjacent to Hudson Strait with a density difference of only 0.13 sigma-t units over a depth of 260 m. Saglek Bank, in the north, was characterized by weak stratification, low surface temperatures (1-3°C), a minimal amount of water less than -1°C and a relatively narrow salinity range (31-33) across the shelf (Fig. 4). In contrast, along the southern-most transect across Hamilton Bank, there was an intense pycnocline at 20 to 40 m depth, surface temperatures were warm (5-9°C), most of the cross-sectional area below the pycnocline was occupied by waters < -1°C and the salinity range lay between 28 and 34 (Fig. 4). Whereas the temperature in the surface layer (0-50 m) waters generally increased southward, below 100 m this pattern was reversed, similar to the findings of Lazier (1982). In the across-shelf direction, relatively warm surface water appeared inshore and off the shelf with cooler waters in the mid-shelf region. The prominent salinity gradient was across-shelf with fresher water inshore (Fig. 3). The lowest salinity waters (< 30) were observed in the southern inshore areas due to the large freshwater inflow from Hamilton Inlet. This creates a strong, stable stratification in the upper layers.

Nutrients

Nitrates are generally considered to be the limiting nutrient to primary production during the summer in northern waters (Grainger, 1975). High nitrate levels (depth integrated over the top 50 m) were observed near Hudson Strait and appear to spread out onto Saglek Bank (Fig. 5). Other nitrate maxima occur along the continental slope off southeastern Nain Bank and Hamilton Bank, and in the marginal trough inshore of Hamilton Bank. These are believed to be a result of local upwelling. The distribution of silicate and phosphate concentrations show similar patterns to the nitrates.

The contrast between vertical nitrate profiles on the northern and southern Labrador Shelf are shown in Fig. 6. On both Saglek and Hamilton Banks surface waters are devoid of nitrates, because of depletion by phytoplankton. In the north, the nutricline tends to be shallower whereas on Hamilton Bank it lies near 50 m depth at the base of the pycnocline (Fig. 4). Nitrate levels below the nutricline are higher on Hamilton Bank than on Saglek. The high depth-integrated (0-50 m) values at both the inshore and offshore edge of Hamilton Bank are due to a shallowing of the pycnocline since zero or low nitrate occurred in near surface waters.

Chlorophyll-a

The highest depth-integrated (0-50 m) chlorophyll-a levels were measured over Saglek Bank (Fig. 7). Elevated levels were also observed to extend and increase in the vicinity of Nain Bank (over the centre and along its southeastern edge at the continental slope), off the eastern edge of Harrison Bank and in the marginal trough inshore of Hamilton Bank. These tend to occur in or adjacent to regions of high near-surface nutrient levels (Fig. 5). Over central Saglek Bank, chlorophyll-a levels were maximum towards the middle of the Bank whereas to the south of the Bank the maximum was shifted towards the continental slope (Fig. 7). Along the transect across Hamilton Bank the chlorophyll-a levels were maximum in the marginal trough adjacent to the inshore slope of the Bank. Although not evident from the depth-averaged chlorophyll-a levels, there was also slightly enhanced chlorophyll-a concentrations observed above the continental slope off Hamilton Bank in the region of higher nutrient levels (Fig. 5).

Biomass Distributions

The abundance estimates of plankters from the size-fractionated water and net samples are reported here in 5 size-classes. These were 1-8 μm (nanoplankton, mostly small flagellates), 16-125 μm (microplankton), 125-1028 μm (mesoplankton dominated by small copepods), 1028-4000 μm (macroplankton consisting of primarily large copepods such as *Calanus)* and 8-16 mm (nekton which included crustaceans, fish larvae and small fish).

The ratio of the maximum to minimum station abundance of the 2 smallest size groups, which are dominated by phytoplankters, varied by up to a factor of 3 over the entire shelf grid. The general pattern of abundance of nanoplankton showed relatively high values in the southern shelf area and on Saglek Bank (Fig. 8a). There was a maximum of just over 20 g wet wt/100^3 to the north of Hamilton Inlet (Stn. 24) and a minimum in the offshore waters just north or 60°N of 5 g wet wt/100^3 (Stn. 51). A bimodal pattern dominated the microplankton with the highest concentrations (>40 g wet wt./100^3) in the north on Saglek Bank (Stns. 45, 49) and in the south in the marginal trough (Stn. 5) inshore of Hamilton Bank (Fig. 8b). High concentrations (>30 g wet wt./100^3) were also observed on Hamilton Bank, off Hamilton Inlet, and in Cartwright and Hopedale Saddles. The bimodal pattern of the microplankton matches closely the chlorophyll-a distribution (Fig. 7) which is expected since phytoplankton dominates the microplankton size group.

The range in abundance of zooplankton was larger than that for phytoplankton, with the ratio of the maximum to minimum station abundance over the entire grid of stations of the next 2 largest size groups being 15-16. The mesoplankton, which was dominated by small copepods, showed two distinct trends (Fig. 8c). The first was a southward decrease from a maximum concentration of 80 g wet wt/100 m^3 near Hudson Strait. The second was a strong offshore gradient with higher values inshore. The macroplankton (primarily large Calanus) also showed a tendency towards decreasing values offshore (Fig. 8d). The maximum concentrations (50 g wet wt./100^3), however, appeared inshore of Makkovik Bank, downstream of Saglek Bank. The nekton abundances were generally low with minimum values in the south and high values on Saglek Bank in the north and along the continental slope (Fig. 8e).

Particle-size Spectra

If the hypothesis of an advective food chain was correct, then the relative importance of the larger-size particles should increase southward. To test this we calculated the average abundance for each size-class along each of 10 cross-shelf transects. These were across Hamilton Bank (stations 3-12), northern Hamilton Bank (12-16), Cartwright Saddle (16-21), Makkovik Bank (21-26), Hopedale Saddle (26-32), Nain Bank (32-37), Okak Bank (37-42), southern Saglek Bank (42-47), central Saglek Bank (47-51) and the northern edge of Saglek Bank (51-54). The mid-point of each transect was identified and the along-shelf distance from their mid-point to that for the Hamilton Bank transect was estimated. The average abundance along the transects for each of the five size-classes was then plotted against the along-shelf distance (Fig. 9). The length of the shelf from Hamilton Bank to Hudson Strait is approximately 1000 km. The along-shelf abundances show the bimodal distribution in the microplankton with maxima in the north and south, maxima at mid-shelf and in the north for the meso- and macroplankton, relatively level concentrations of nanoplankton and low abundance of nekton with a peak in the north.

The abundance as a function of the logarithm of the size, i.e. the particle-size spectra, were plotted for three transects, Hamilton Bank in the south, Makkovik Bank in the central shelf area and the central Saglek Bank in the north (Fig. 10). In the north, high abundance of both phytoplankton (microplankton) and zooplankton (meso- and macroplankton) were observed. At Makkovik Bank there was a shift towards a relative increase in abundance of the larger size-classes but at Hamilton Bank the concentrations of the larger plankton were low.

Pseudocalanus Distributions

To further test the possibility of an advective food chain, the distributions of *Pseudocalanus* development stages were grouped into two categories to determine if their was an indication of a southward movement with progressively later life stages. No significant difference in distribution was observed between copepodites (C I-IV) and adults (C V-VI) (Fig. 11a,b).

DISCUSSION

The low degree of stratification and high nutrient content on the northern Labrador Shelf measured during our cruise reconfirm the affect of the Hudson Strait outflow on the physical and chemical properties of the waters on the northern Labrador Shelf during the summer (Kollmeyer et al. 1967; Lazier 1982; Sutcliffe et al. 1983). The high chlorophyll-a and microplankton biomass on the northern Labrador Shelf indicate intense primary production in response to the nutrient flux from Hudson Strait and are consistent with the first part of the hypothesis as proposed by Sutcliffe et al. (1983). An indication of how representative of the entire summer our cruise results were can be obtained from satellite imagery of ocean colour. This senses a weighted average of the relative phytoplankton biomass principally over the first optical attenuation depth (Sathyendranath and Platt 1989) which in northern coastal waters is approximately the upper 10 m or so of the water column (G. Harrison, Bedford Institute, personal communication). Satellite data from NASA's Coastal Zone Color Scanner (CZCS) taken between 1978 and 1986 have been processed for monthly images of each of the 9 years, as well as monthly composites over all of the years (provided by G. Harrison, Bedford Institute). They show highest (relative) phytoplankton biomass on the northern Labrador Shelf during the summer months, confirming the results of the present study. Concentrations of phytoplankton were also observed during our cruise near the inshore edge of Hamilton Bank. Most of this biomass was located near the bottom of the pycnocline at about 30-50 m and contrasts our observations on Saglek Bank where the highest biomass was found in the upper 20 m or so. This peak in biomass near Hamilton Bank appears to be situated in a region of upwelling, as suggested by the rising up of sigma-t and nutrient isopeths (Figs. 4 and 6, respectively). It was not observed in the CZCS data because it is beyond the depth range of the satellite sensor.

Does the high phytoplankton abundance on the northern Labrador Shelf support increased zooplankton production further downstream as predicted by the advective food chain hypothesis? The macroplankton, consisting of mostly large copepods, were observed to have a peak abundance downstream of Saglek Bank in the inshore regions of the shelf, consistent with the advective hypothesis. However, there was a relatively high standing crop of both meso- and macroplankton on Saglek Bank and no evidence of zooplankton being transported southward to Hamilton Bank in large numbers at this time of the year. The development times of many of the larger zooplankton (macroplankton) are of the order of 1-2 y, thus they may occupy the central shelf area feeding opportunistically in summer, while the major growth could be associated with feeding upon the spring bloom in June when the ice normally retreats from the Labrador Shelf. Satellite imagery do show a spring bloom with the retreat of the ice.

Data collected on nekton abundance are less reliable than the other size-classes because during the day those that migrate vertically to near the bottom may not have been well sampled. In spite of this complication, there was a clear trend in abundance on the shelf, i.e. a peak in the north and very low values on the shelf south of Saglek Bank. There were also high concentrations near the shelf break due mainly to large catches of mesopelagics such as lantern-fish. These may have been feeding on the phytoplankton biomass accumulated at the edge of the shelf.

In summary, although the peak in the macroplankton does appear downstream of Saglek Bank, an area of high primary production, the advective food chain hypothesis (Sutcliffe et al. 1983) is not strongly supported by the distribution of other trophic levels. The hypothesis suggested production was advected via the food chain along the Labrador Shelf to Hamilton Bank and eventually onto the northern Newfoundland Shelf. The zooplankton biomass on Hamilton Bank and vicinity at the time of our collections was relatively low. While this low abundance could possibly be explained by increased predation, the nekton which feeds upon the zooplankton was in low concentrations. Also, the hypothesis can not account for the relatively high abundance of zooplankton on the northern Labrador Shelf. Finally, development stages of *Pseudocalanus* showed no evidence of distributional shifts southward with increasing age.

Why would zooplankton abundance be high over Saglek Bank? Sutcliffe et al. (1983) assumed a southward flow over the entire shelf and at the shelf break. Current meter observations obtained since that paper was published show that the residual currents on the banks, including Saglek, are relatively weak (Fissel and Lemon 1991). This implies a longer residence time for the water on the banks relative to the water in the marginal troughs and along the continental slope. It appears as if these residence times of 1 to 2 months are of sufficient length for, at least, the small zooplankton to develop locally. Another contributing factor to the high zooplankton abundance may be advection from Hudson Strait.

The objective of Sutcliffe et al. (1983) was to explain the high fish biomass and production on the southern Labrador and northern Newfoundland Shelf. If a large-scale advective food chain propagating southward over the Labrador Shelf does not persist what does support the fish production in the south? Much of this production occurs in the vicinity of Hamilton Bank and until recently consisted of primarily cod. The cod feed upon capelin which in turn prey upon small fish and large zooplankton. This food chain may be supported by local phytoplankton production generated by upwelling processes at both the shelf break and at the inshore edge of Hamilton Bank and is supported by observations of nutrients, chlorophyll-a and phytoplankton biomass obtained during the cruise. There was also high phytoplankton biomass nearshore off Hamilton Inlet which may be related to the effects of freshwater runoff.

CONCLUSIONS

On the basis of the September, 1985, cruise to the Labrador Shelf we have reached the following conclusions.

(1) The outflow from Hudson Strait carries nutrient enriched waters to the northern Labrador Shelf which results in increased phytoplankton production and high standing stocks.

(2) This production supports local zooplankton production on Saglek Bank although some zooplankton may have been advected with nutrient rich waters from Hudson Strait.

(3) Evidence that this primary production on the northern Labrador Shelf is advected southward supporting a "conveyor belt" food chain, as proposed by Sutcliffe et al. (1983) is weak although peak macroplankton abundance does occur downstream of Saglek Bank in nearshore stations from Nain to Hamilton Inlet.

(4) High phytoplankton biomass in the vicintiy of Hamilton Bank is most likely a response to local upwelling processes.

ACKNOWLEDGEMENTS

Thanks to the many individuals who helped during and after the cruise, especially to: R. Sheldon and N. Prouse who provided the Coulter counter data; P. Cranford for the nutrient analysis; J. McRuer, D. Reimer, P. Vass and T. Palmeter for collection of the net samples; C. Simmons for the chlorophyll-a analysis; and L. Petrie, P. Larouche, C. Fitzpatrick, P. Stead and E. Bonneau with help in collecting the hydrographic data. We also gratefully acknowledge L. Petrie for drafting the figures and A. Orr for her part in the analysis of the biomass data.

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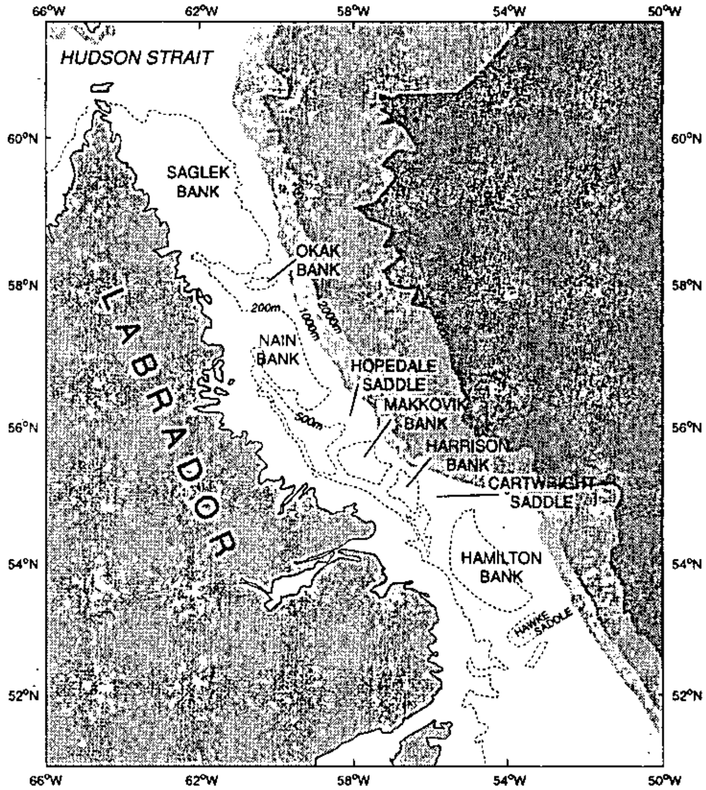

Fig. 1. Labrador Shelf showing topographic features.

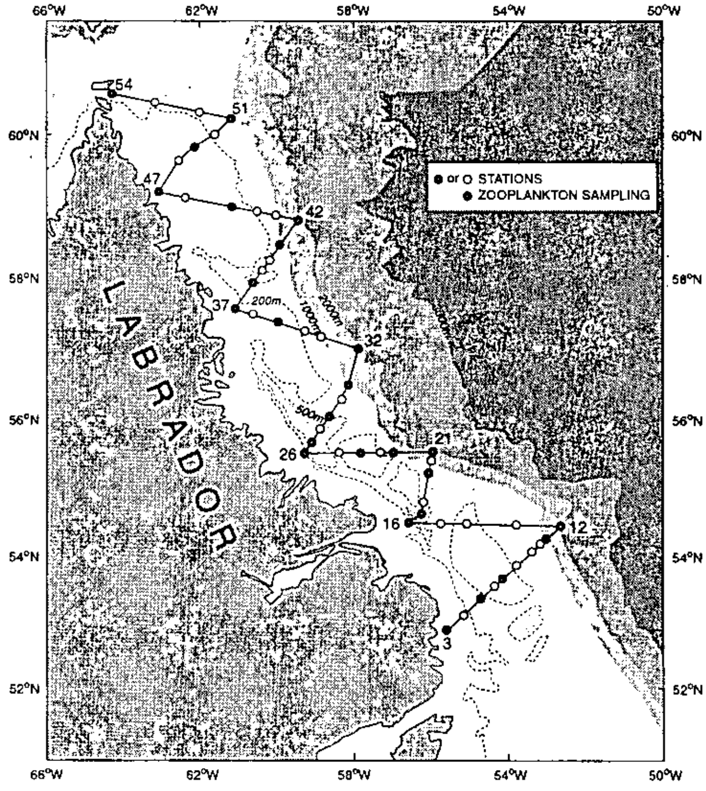

Fig. 2. The station locations occupied during September, 1985. Hydrographic, nutrient and Coulter counter measurements were taken at all stations and plankton net samples at the stations marked by a solid dot.

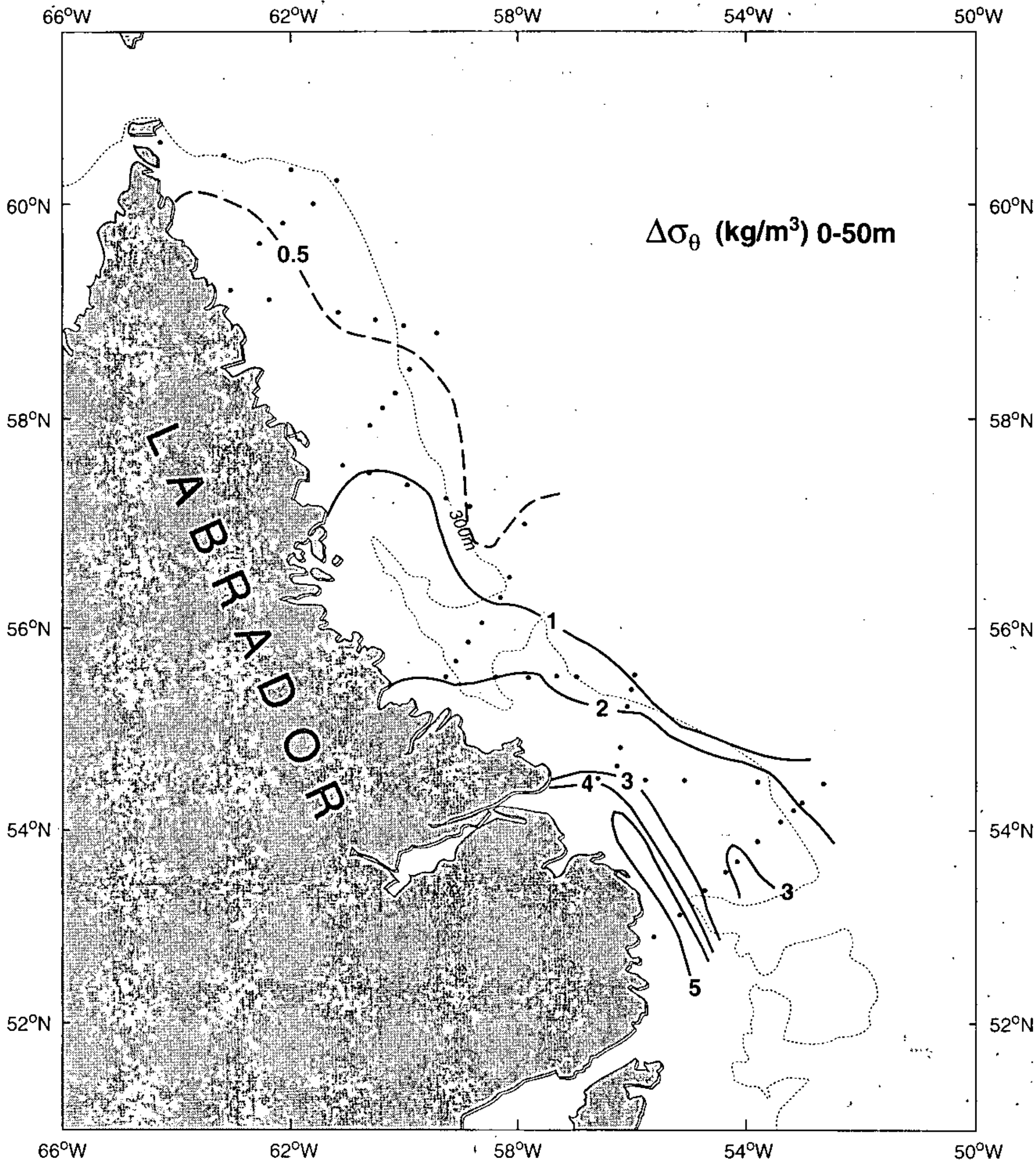

Fig. 3. The difference in σ_θ between the surface and 50m. The dots indicate the stations where density data were collected.

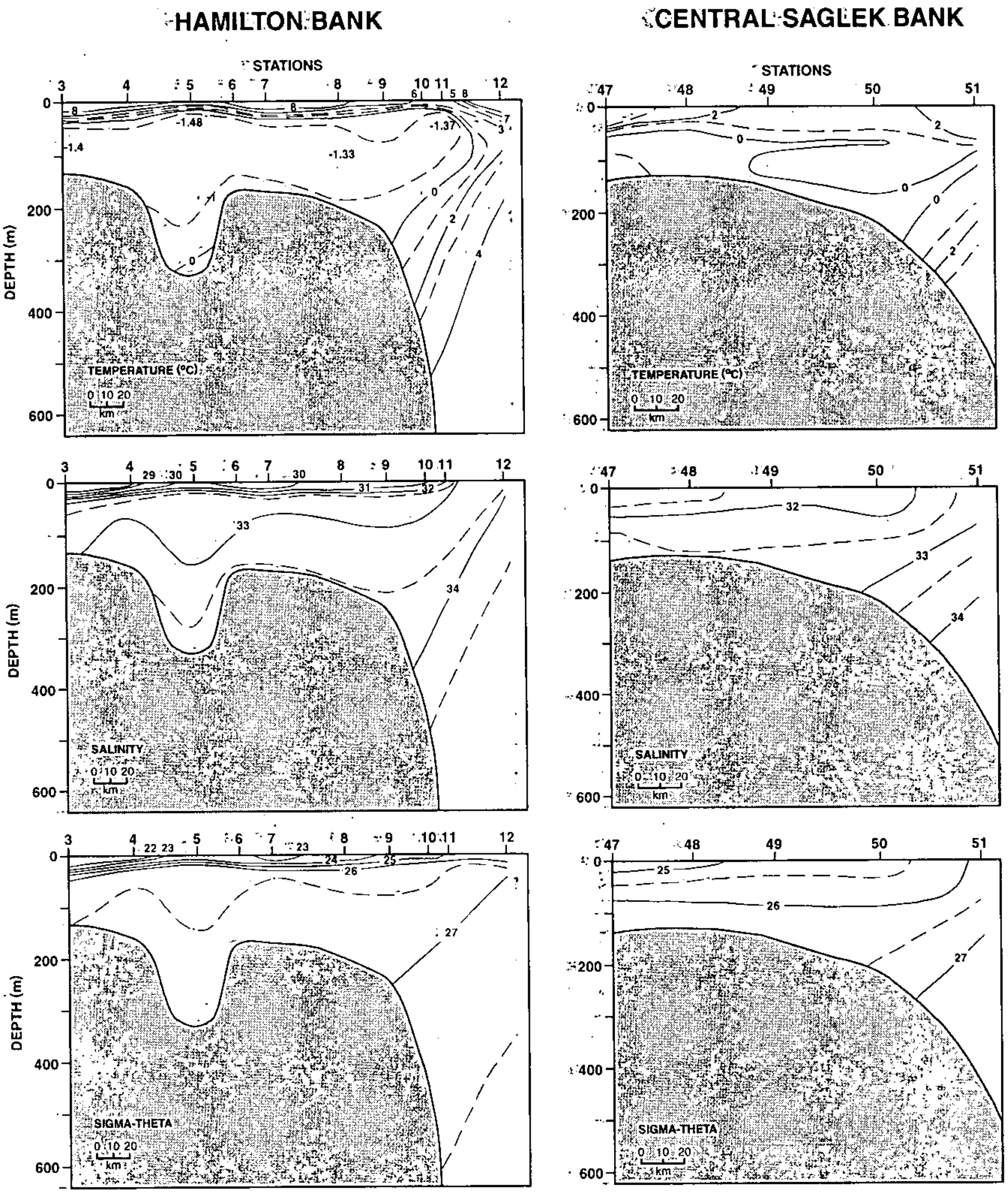

Fig. 4. The temperature, salinity, and sigma-theta transects across Hamilton Bank and central Saglek Bank.

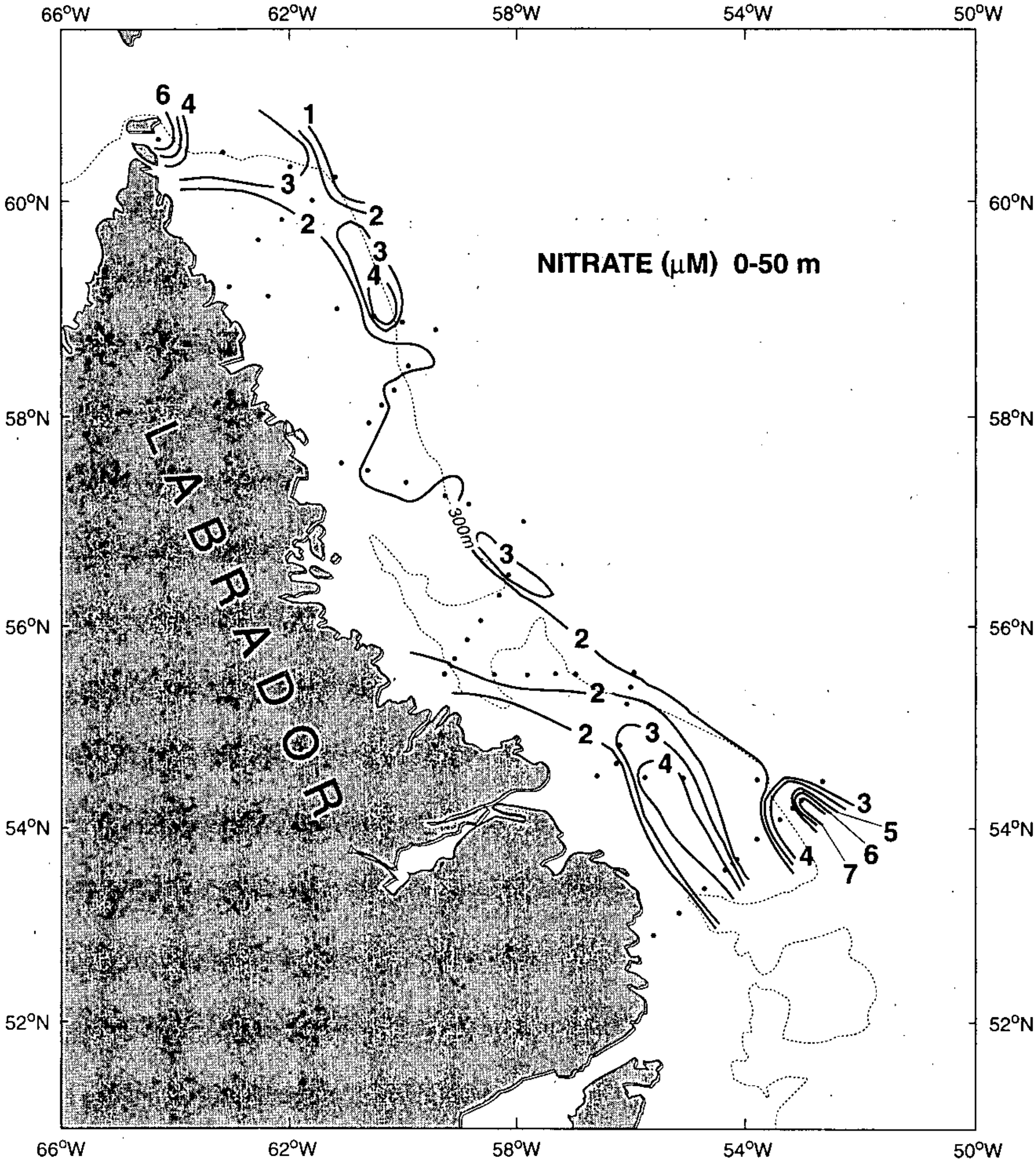

Fig. 5. The depth-averaged nitrate over the top 50m. The dots indicate the stations where nitrate data were collected.

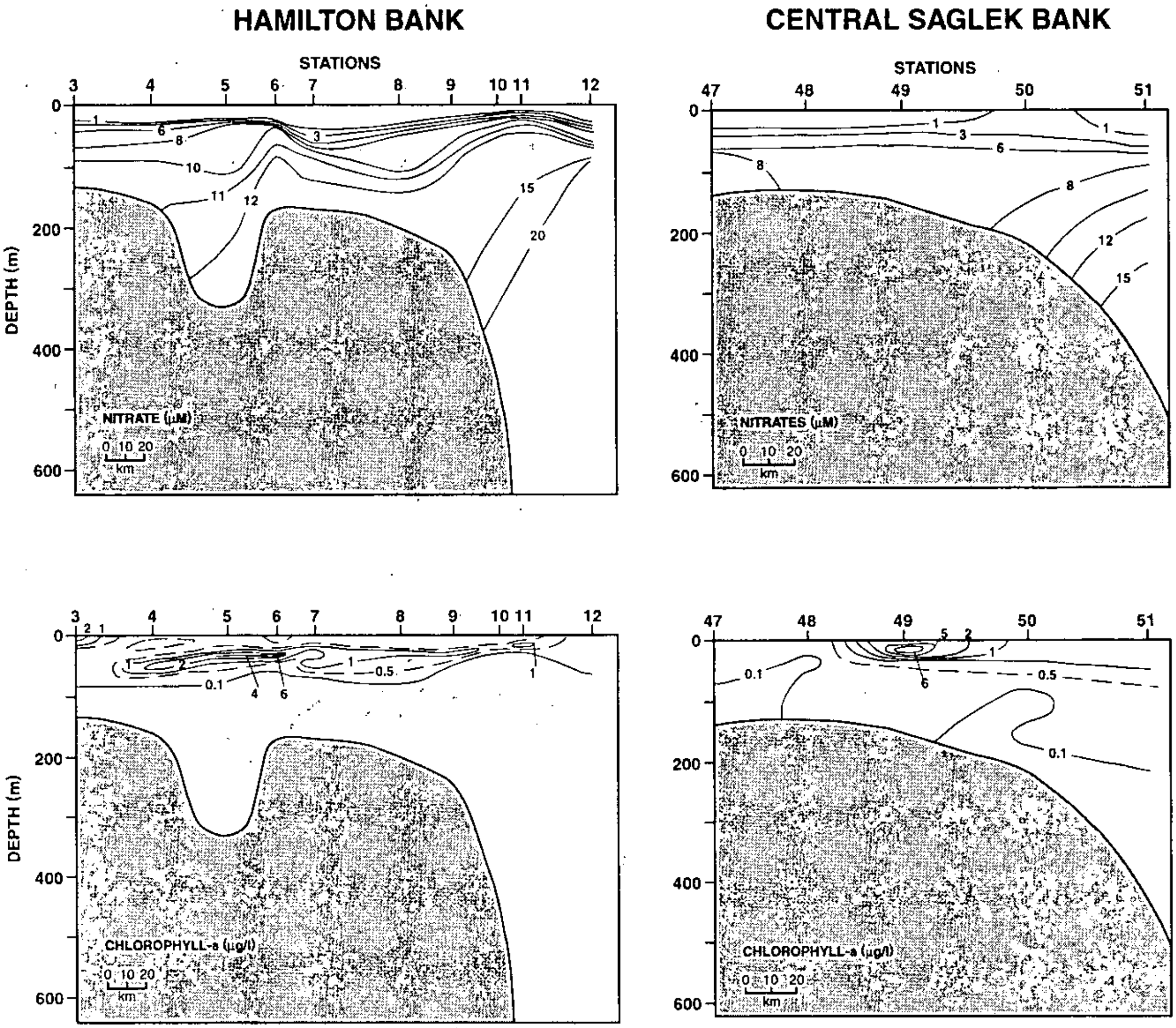

Fig. 6. The nitrate and chlorophyll-a transects across Hamilton Bank and central Saglek Bank.

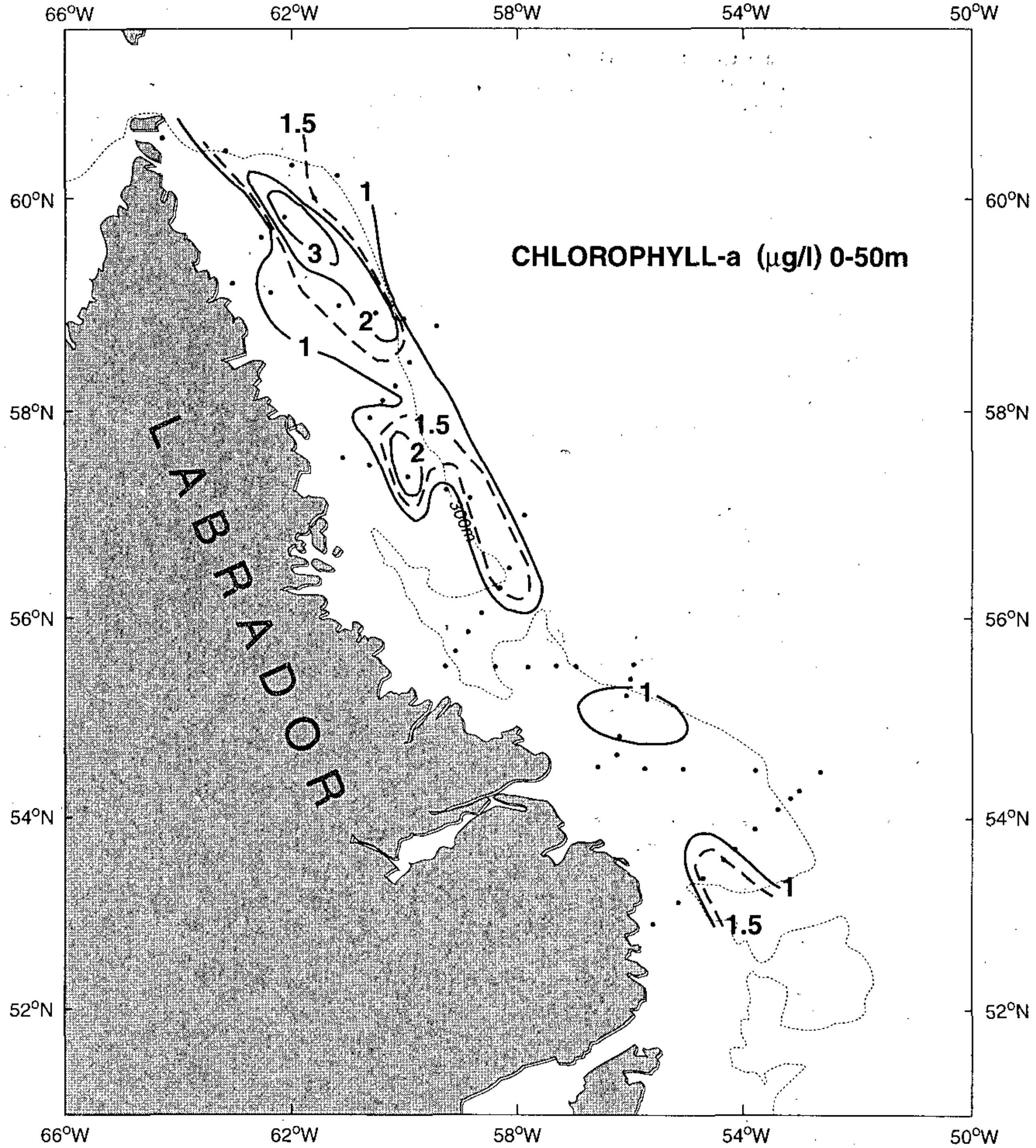

Fig. 7. The depth-averaged chlorophyll-a over the top 50m. The dots indicate the stations where chlorophyll-a data were collected.

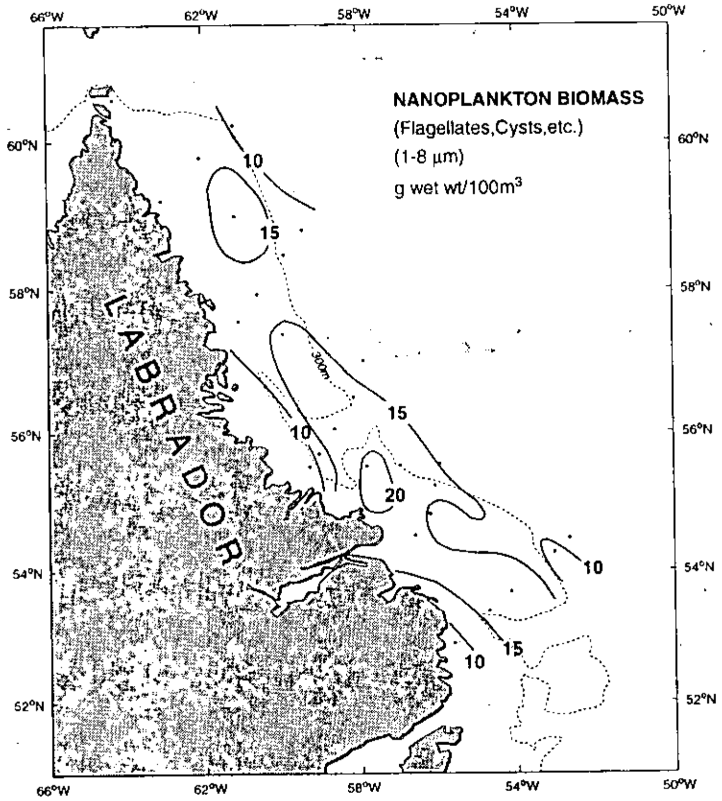

Fig. 8a. The biomass of nanoplankton. The dots indicate the stations where plankton data were collected.

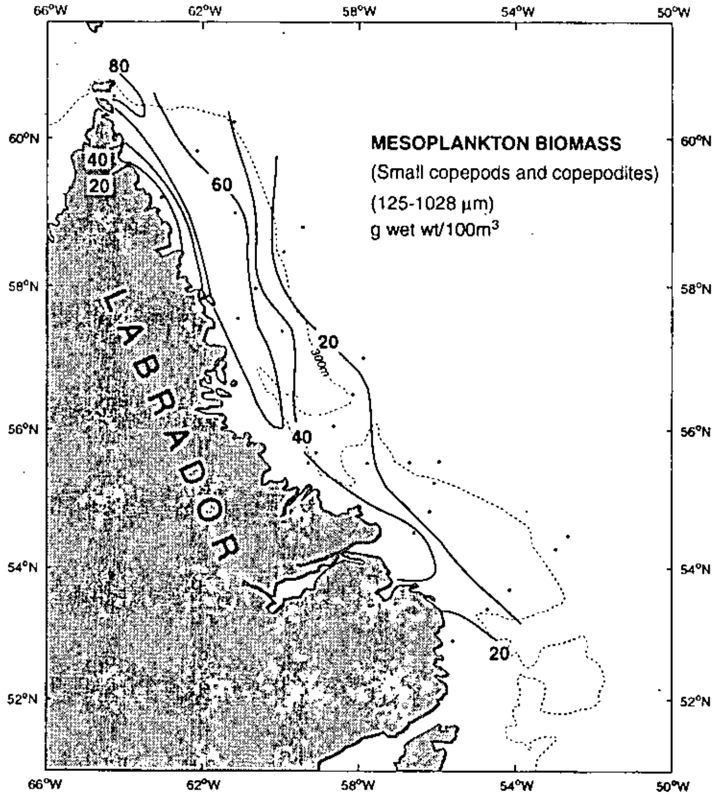

Fig. 8c. The biomass of mesoplankton. The dots indicate the stations where plankton data were collected.

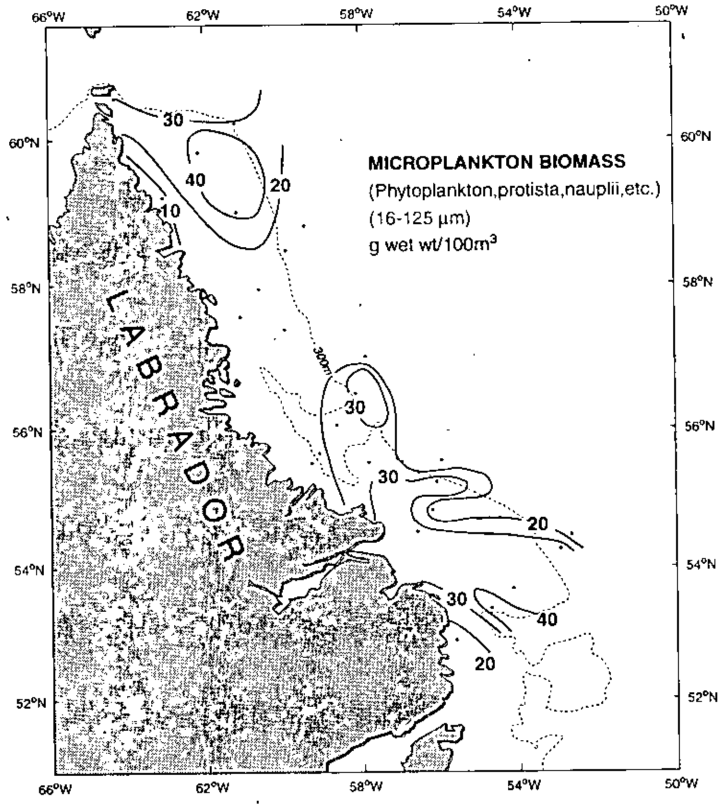

Fig. 8b. The biomass of microplankton. The dots indicate the stations where plankton data were collected.

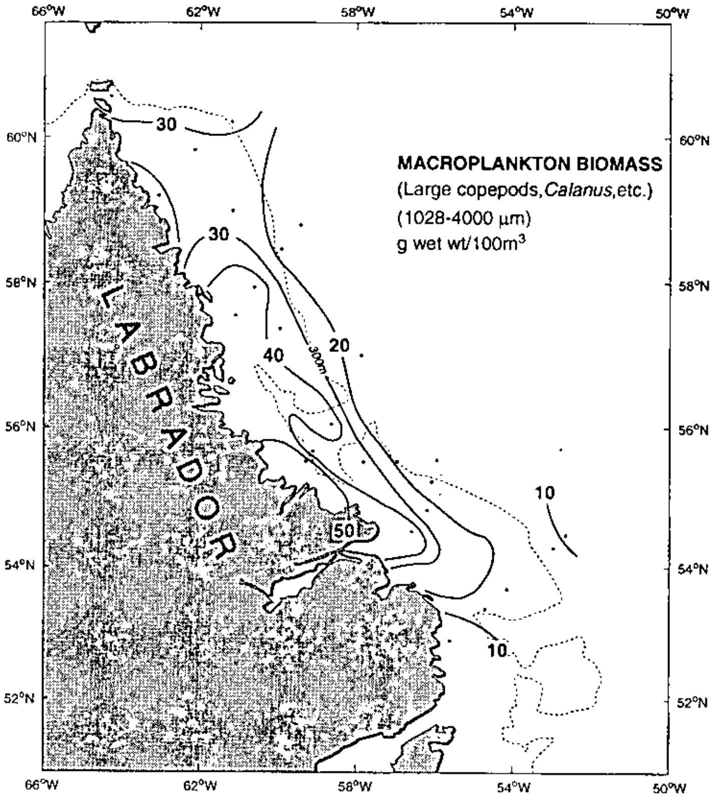

Fig. 8d. The biomass of macroplankton. The dots indicate the stations where plankton data were collected.

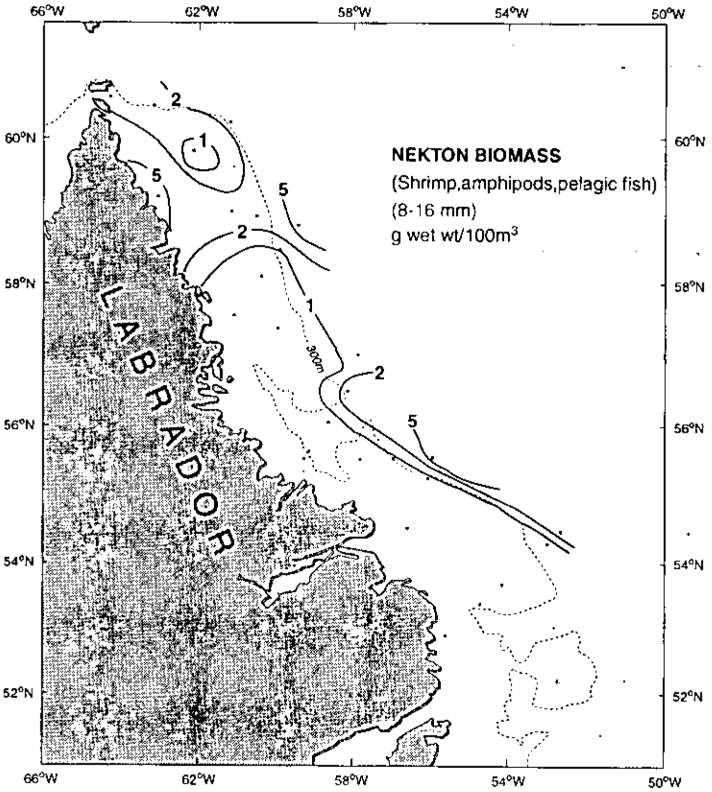

Fig. 8c. The biomass of nekton. The dots indicate the stations where plankton data were collected.

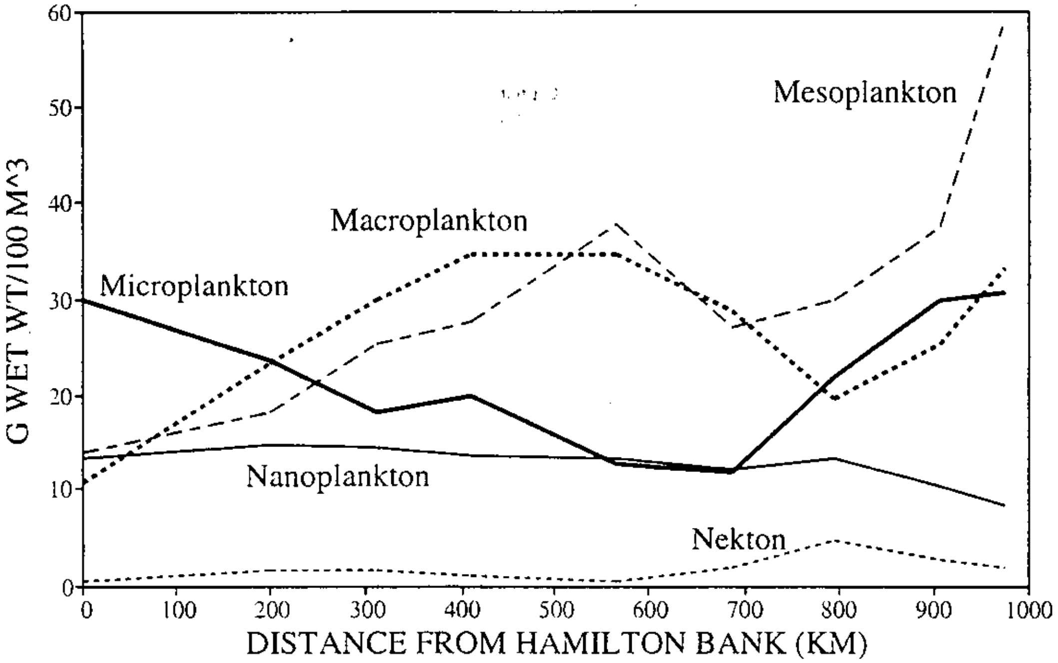

Fig. 9. Plankton abundance, averaged across the shelf, as a function of alongshelf distance from Hamilton Bank.

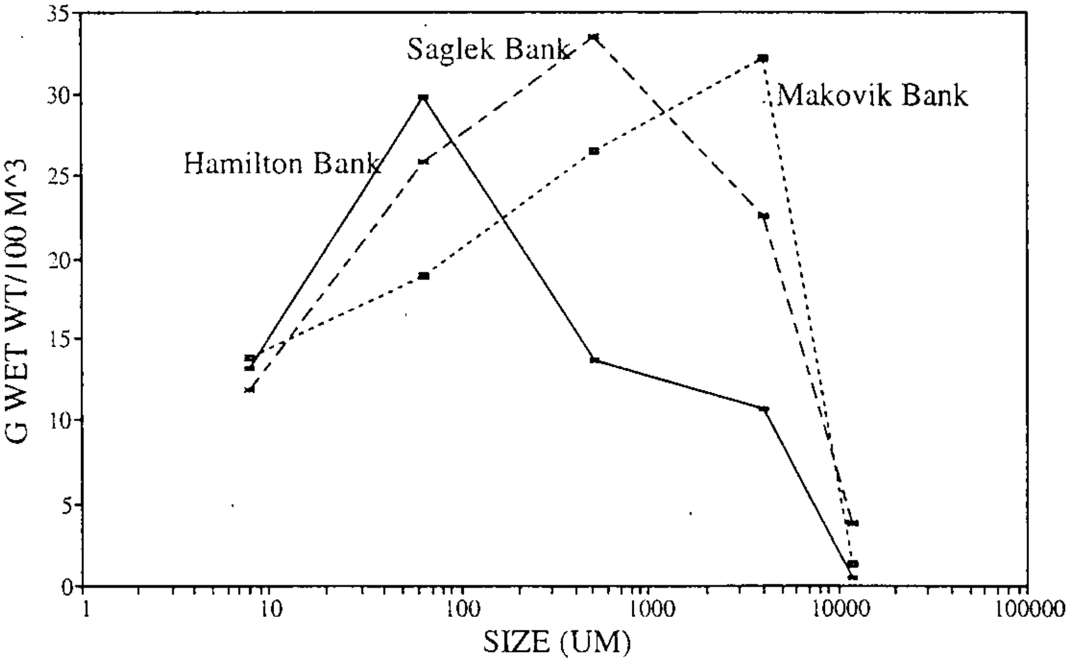

Fig. 10. The particle-size spectra from transects across Hamilton Bank, Makkovik Bank and Saglek Banks.

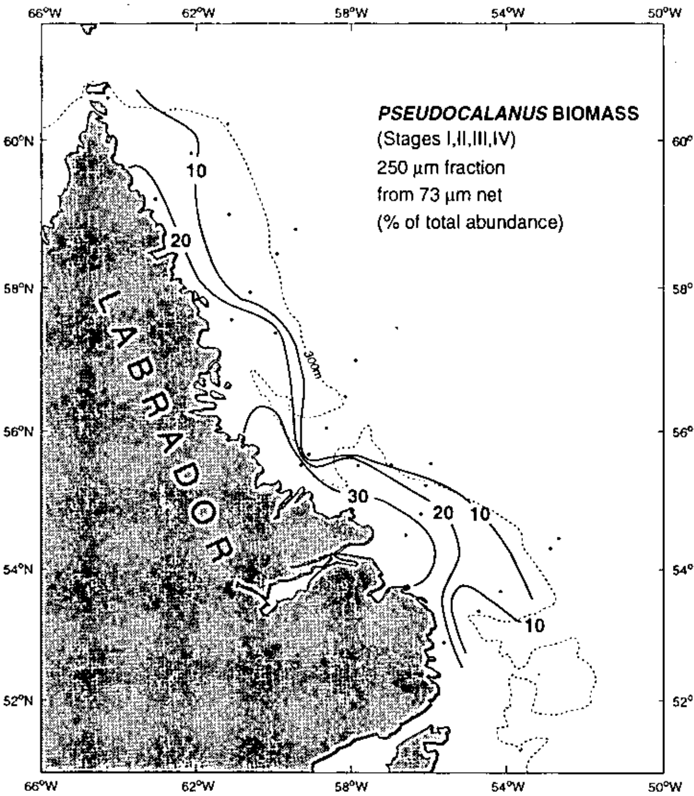

Fig. 11a. The biomass of stages I-IV of *Pseudocalanus*, expressed as a percentage of the total biomass for this size-class.

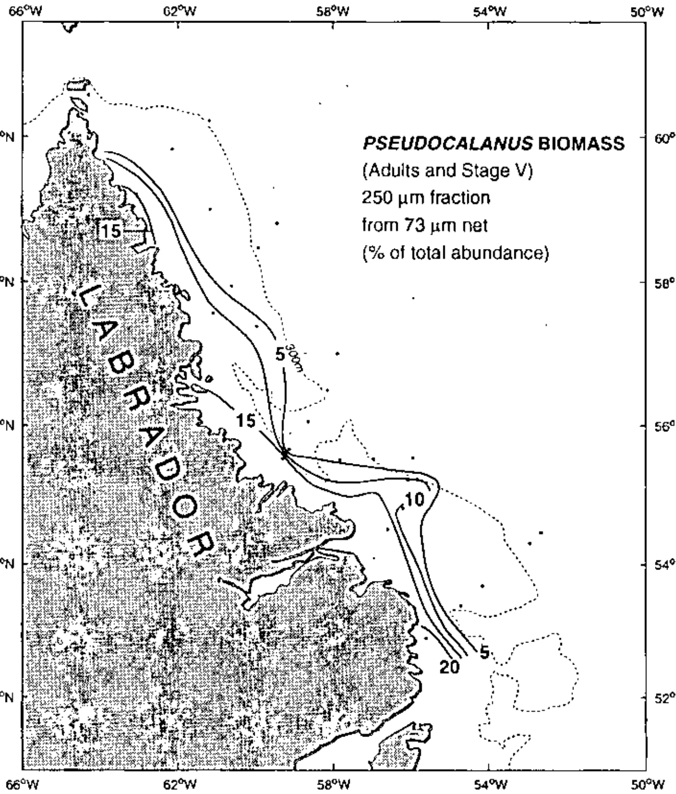

Fig. 11b. The biomass of stage V and adult *Pseudocalanus*, expressed as a percentage of the total biomass for this size-class.