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Biological and Chemical Oceanographic conditions on the Newfoundland Shelf during 2000 with comparisons with earlier observations

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ABSTRACT

We review the information concerning the seasonal and internannual variations in the concentrations of chlorophyll *a*, nitrates, phosphates and silicates as well as the abundance of major taxa of zooplankton measured from Station 27 and standard oceanographic transects on the Newfoundland Shelf. We focus on the conditions during 2000 but contrast those observations with previous information from the period of 1996-1999 with particular emphasis on the last year. Nutrient levels were comparable to the previous year although there was some evidence of an influx of waters with higher nutrient concentrations along the bottom during late Fall. The Spring phytoplankton bloom was restricted to the upper 60m of the water column but the overall intensity was slightly greater than in 1999. In contrast to 1999, there were no subsurface phytoplankton blooms during the Summer of 2000 and we did not find evidence of a small Fall bloom. Overall, the zooplankton community was similar in abundance and composition to that observed in 1999. There was some indication of a greater abundance of *Oithona similis* and *Pseudocalanus* sp., but this may have reflected a competitive balance between these two numerically dominant species. The abundance of *Calanus finmachicus* and *C. glacialis* was similar to that observed in previous years but the overall abundance of large calanoid nauplii, most likely produced by these two species, was approximately twice that observed in 1999 at both Station 27 and across the entire Newfoundland Shelf.

RÉSUMÉ

La présente étude passe en revue les données sur les variations saisonnières et interannuelles des teneurs en chlorophylle *a*, en nitrates, en phosphates et en silicates, ainsi que de l'abondance du zooplancton récolté à la station 27 et le long de transects océanographiques normalisés de la plate-forme de Terre-Neuve. Bien que l'accent soit mis sur les conditions de 2000, les observations sont comparées aux données recueillies de 1996 à 1999, particulièrement celles de 1999. Les teneurs en éléments nutritifs de 2000 sont comparables à celles de 1999, mais les analyses indiquent la présence d’eaux riches en éléments nutritifs long du fond à la fin de l'automne. La floraison printanière du phytoplancton s’est établi dans les premiers 60 m de la colonne d'eau et elle était en général légèrement plus intense qu'en 1999. Contrairement à la saison 1999, il n'y a pas eu de floraison phytoplanctonique sous les 60 m pendant l'été 2000 et aucun signe d'une floraison automnale n'a été observé. En 2000, l'abondance et la composition de la communauté zooplanctonique se rapprochaient de celles observées en 1999. L’abondance de *Oithona similis* et de *Pseudocalanus* sp. était plus forte en 2000, mais cela peut refléter un équilibre dans la compétition entre ces deux espèces les plus abondantes. L'abondance de *Calanus finmarchicus* et de *C. glacialis* était semblable à celle observée par les années passées, alors que l'abondance globale des nauplii de grande taille, issus très probablement de ces deux espèces, était environ deux fois celle observée en 1999 à la station 27 et à l'échelle du plateau de Terre-Neuve.

INTRODUCTION

We review the optical, chemical, and biological oceangraphic conditions on the Newfoundland and Labrador Shelf during 2000. More frequent detailed sampling at station 27 and the completion of three surveys of the Newfoundland Shelf during the year provided good spatial and temporal series coverage of standard variables. This provides a good basis for comparison with previous years. Collections and standard measurements of nutrient and chlorophyll *a* concentrations as well as phyto- and zooplankton abundance are based on protocols outlined by the Steering Committee of the Atlantic Zonal Monitoring Program (AZMP). A number of non-standard AZMP variables are also presented for information. Protocols for additional measures are briefly described in the text. Observations presented in this document are based on surveys listed in Table 1 and Figure 1.

FIXED STATION-IRRADIANCE

The availability of light for photosynthesis in an aquatic ecosystem, is determined by the penetration of the light field (Kirk 1994). Irradiance data was collected using a quantum PAR (photosynthetic available radiation; 400-720 nm) irradiance sensor (Biospherical QSP-200PD) attached to a Seabird SBE-25 profiling CTD. Sources of potential error in the irradiance data, principally cloud effects, wave action, and ship's influence were not corrected in our data. Downward irradiance (E_d) (µmol quanta m^{-2} s^{-1}) decreases exponentially with depth according to:

$$E_d(z) = E_d(0)\, e^{-K_d z} \qquad \text{(Kirk 1994)}$$

where $E_d(z)$ and $E_d(0)$ are the values of downward irradiance at z m and just below the surface, respectively, and K_d is the downward vertical attenuation coeffcient. From each irradiance profile, we estimated the downward vertical attenuation coefficient for PAR (K_{d_PAR}) from the linear regression of ln $E_d(z)$ versus depth. The plots of ln $E_d(z)$ versus depth are typically biphasic, therefore we estimated K_d using the linear regression coefficient for the upper linear portion of the curve that normally extended to depth of 50-100m. We compared values of K_d with observations of Sechhi disk and chlorophyll *a* measures using:

$$K_{d\_secchi}\ (m^{-1}) = 1.44 / Zsd \qquad \text{(Kirk 1994)}$$

$$K_{d\_chla}\ (m^{-1}) = 0.027\ m^{-1} + 0.015\ m^{-1} + B(z)*0.04\ m^{-1} \qquad \text{(Platt } et\ al. \text{ 1988)}$$

where Zsd = depth in m at which the Secchi disk disappears from view, and B(z) is the concentration of chlorophyll *a* (mg m^{-3}) at z m.

In general, the time series of different measures of the attenuation coefficient (K_d) showed similar trends throughout the year (Figure 2a). All measures of attenuation increased rapidly by two-fold during the onset of the spring bloom from initial background levels of ca. 0.1 m^{-1}. After cessation of the spring bloom, attenuation rates returned to near background levels until the Fall period, when estimated K_d values derived from PAR and Secchi disk measures increased slightly, but, was not apparent for estimates derived from chlorophyll *a* concentrations, which remained near background levels. The seasonal variation in the attenuation coefficient mirrored in the integrated chlorophyll *a* series (Figure 2b). Seasonal variation was observed in the stratification index (density 50m – density (surface)) / 50m) and mixed layer depth (depth of the centre of the pycnocline) time series at station 27 (Figure 2c). Stratification remained low during Winter and Spring, increased slowly throughtout the late Spring and early Summer, and reached at maximum during late Summer. Stratification decreased thereafter, reaching winter-time values by late Fall. Mixed layer depths were generally >50m during Winter and Fall and shallowed below 50m during the Spring and Summer periods. It was apparent that the timing of the Spring bloom coincided with shallowing of the mixed layer and preceeded the increase in stratification. Making the assumption that K_{d_PAR} is constant with depth, the estimate of euphotic depth (the depth of the 1% light level) is given by:

$$Z_{eu}\,(m) = 4.6 / K_{d\_PAR} \qquad \text{(Kirk 1994)}$$

The time series of euphotic depth at station 27 varied seasonally with shallow depths estimated for the Spring and Fall period (ca. 20-40m) while deeper values (ca. 50-80m) were estimated during the Summer period (Figure 2d). On average, the depth of the euphotic layer derived from K_{d_PAR} during 2000 is ca. 58m.

FIXED STATION-NUTRIENTS

We examine the 2000 time series of major nutrients including combined nitrate-nitrite (henceforth referred to as nitrate), total ortho-phosphate (phosphate), and silicate at station 27. Nutrient concentrations were quantified using a Technicon Autoanalyzer system according to procedures in Strain and Clement (1996).

Concentrations of nitrate and silicate were depleted in April 2000 to nearly undetectable levels (< 0.1 μM) in the upper 40m (Figure 3d, 3f). Concentrations of phosphate reached low levels during a brief 10 d period in July (Figure 3e). Concentrations of nitrate and silicate in the upper layer remained at depleted levels until October when nominal increases were observed. After depletion of nitrate and silicate were observed in April, the nutricline formed at ca. 40m and deepened through till the Fall period when mixing resulted in a rapid shoaling. Nitrate concentrations in the deeper layers (> 40m) increased throughout the time series reaching peak levels in excess of 10 μM, phosphate concentrations fluctuated between 1-2 μM, while silicate concentrations showed a pattern similar to that of nitrate and reached peak levels in excess of 15 μM (Figure 3d-f). Comparisons between the 2000 and 1999 series for major nutrients were somewhat difficult due to large gaps in the latter series, but nitrate and silicate concentrations appear to have been depleted earlier and longer during 2000, and Fall mixing was initiated earlier and in greater magnitude in 1999 compared to 2000. The nutricline layer was deeper (particularly for silicate) in 1999 compared to 2000. Phosphate concentrations attained similar concentrations between years, but, Fall overturn occurred earlier in 1999. There is some indication that the levels of nutrients near the bottom were higher in 2000 than in 1999, but the increase appears to be relatively small (~1-2 μM for nitrate and silicate). The concentration of nitrate versus silicate at station 27 during 1999-2000 indicated the uptake of silicate by diatoms was important during all seasons, particularly, during the spring period (Figure 4). The intercepts indicated that both nitrate and silicate may limit phytoplankton growth in the inshore coastal branch of the Labrador current during the spring and summer periods. In contrast, phytoplankton growth during the fall period appears to be limited largely by nitrate (Figure 4). Rates of utilization of nitrate and silicate varied between years and seasons at Station 27. Rates of utilization were highest during Spring in 1999 compared to Summer and Fall in 2000 at Station 27. Rates also differed geographically with higher values observed for the fixed station compared to offshore transect stations. This was particularly evident during 2000 where large differences between Station 27 and transect stations were observed as compared to the 1999 period (Figure 4).

FIXED STATION-CHLOROPHYLL / PHYTOPLANKTON

A higher sampling frequency during year 2000 allowed a more detailed investigation into phytoplankton dynamics at Station 27 compared to previous years. Concentrations of chlorophyll *a* were generally less than 1 mg m^{-3} throughout the Winter (Jan.-Mar) period (Figure 5a). The Spring bloom in 2000 was initiated in early April and persisted for ca. 40 days. Chlorophyll *a* concentrations during the bloom exceeded 10 mg m^{-3} and were confined to the upper 50m. A deep chlorophyll maximum layer was detected at 40m about 20 days after the primary bloom, indicating sinking of phytoplankton cells. The activity of the phytoplankton assemblage in the deep chlorophyll maximum layer at this time would be limited due to irradiance levels approaching the 1% light level (Figure 2d). There was no evidence of Summer or Fall blooms from May through Dec., when chlorophyll *a* concentrations were generally less than 1 mg m^{-3} throughout the water column. Although the data are limited during the 1999 period, there is evidence of a larger scale Spring bloom, with the occurrence of episodic blooms during the Summer period, and the formation and persistence of a deep chlorophyll maximum layer, which was not apparent at Station 27 during 2000 (Figure 5b).

To summarize the chlorophyll profiles collected at Station 27 during 2000, the vertical structure of phytoplankton biomass (chlorophyll a) can be characterized using a shifted Gaussian formulation:

$$B(z) = B_o + (h / (\sigma\sqrt{2\pi})\exp[- (z- z_m)^2/2\sigma^2] \qquad \text{(Platt } et\ al. \text{ 1988)}$$

where B_o is the background biomass (mg m^{-3}), h is the total biomass above background (mg m^{-2}), σ is the standard deviation (m), z_m is the depth of the chlorophyll maximum (m). The model was fit to both the fluorescence (continuous) data collected from the CTD casts as well as the measurements taken from water samples collected at the fixed depths sampled at Station 27. The time series of background (B_o) fluorescence and chlorophyll *a* concentrations were highly variable, with higher values observed during Winter-Spring compared to Summer-Fall periods (Figure 6a). The trends in the biomass (h) parameter estimates for fluoresence and chlorophyll *a* were similar during the Winter-Spring period but, showed somewhat different trends during the Summer-Fall period (Figure 6b). A smaller secondary peak was observed in the chlorophyll *a* biomass series during the Summer period, while the fluorescence series showed secondary peaks in the early and late Fall periods which were not apparent in the integrated chlorophyll series (Figure 2b). Thickness of the chlorophyll maximum, given by the σ parameter, was maximal during the Winter and Fall periods and minimal during Spring and Summer periods (Figure 6c). In general, both fluorescence and chlorophyll *a* parameter estimates for the depth of chlorophyll maximum were in agreement. The chlorophyll maximum was generally found at a depth of

~50m during the first half of the year, after which there was a overall shoaling towards the surface, when it was well above 30 m and often peaked at the surface (Figure 6d).

The cell densities of major taxonomic groups consisting of diatoms, dinoflagellates and flagellates were investigated at near-monthly intervals at Station 27. Diatoms reached cell densities in excess of 2.5 x 10^6 cells L^{-1} during Spring, contributing 40 % of the total phytoplankton (Figure 7a). A secondary peak in the concentration of diatoms was observed during July, representing 20 % of the total. The concentrations of dinoflagellates were typically smaller by an order of magnitude, but persisted throughout the year, representing less than 5 % of the total phytoplankton (Figure 7b). The flagellates were the dominant group by numbers reaching concentrations in excess of 4 x 10^6 cells L^{-1} and contributed up to 95 % of the total (Figure 7c). With the exception of the Spring period, flagellates were the dominant members of the phytoplankton assemblage at Station 27 throughout 2000 (Figure 7d). Given the large number of different taxa in the flagellates, we further examined the time trends in the major groups (Figure 7). The Chyrsophytes, Prymnesiophytes, Choanoflagellates and unidentified biflagellates groups contributed to the bulk of the Spring bloom. The Prymnesiophytes, Prasinophytes and unidentified biflagellates were the dominant Summer taxa, while Cryptophytes, Chrysophytes, Prymnesiophytes, Prasinophytes, and unidentified biflagellates make up the bulk of the Fall taxa.

FIXED STATION-PRIMARY PRODUCTION

Measurement of primary production was initiated during Summer 2000 at station 27 using the C^{14} technique (Steemann Nielsen 1952).

Measurement of specific production P^b and irradiance E_d PAR were conducted in the laboratory using a custom-built photosynthetron (CHPT Inc., Lewes, DE, USA, see Lewis and Smith (1983) for general description of system and methods). Seawater samples were collected at 10m using a 5L Niskin bottle and transferred back to the laboratory within 1.5 h. Light was provided by two ENH-type tungsten-halogen quartz projection lamps directed through a heat filter (solution of copper sulfate 20 g L^{-1}) to remove much of the higher (red) wavelength emission. This allowed a more natural light spectra to be generated in the photosynthetron. Irradiance levels ranged between 0 and 2500 μmol photons m^{-2} s^{-1} and were varied across the manifold with the use of neutral density filters. Photosynthetically active radiation (PAR) was logged (Li-Cor model LI-1400) in each manifold position before and after incubations using a Li-Cor 2π quantum PAR sensor (Li-Cor LI-190SA). Samples were inoculated with ^{14}C-bicarbonate (ICN Pharmaceuticals Inc.) and aliqouts of 5ml were dispensed into 22ml-glass acid-cleaned scintillation vials in a temperature regulated ($\pm$ 1^{o}C) aluminium manifold at near *in-situ* levels. Photosynthesis-irradiance curves were generated using a manifold holding 24 vials. Incubations were conducted for 60 minutes and were terminated by adding buffered Formalin to each vial. Unincorporated inorganic carbon was expelled by adding 800 ul of 6N HCl and shaking samples in a fumehood for a minimum of 90 min. Measurement of specific production (P^b) and irradiance (E_d PAR) were used to estimate photosynthetic parameters given by uptake of sodium bicarbonate C^{14} and corrected for total dissolved inorganic carbon (DIC) using:

$P^b = P_s (1-e^{-\alpha \, Ed / Ps}) e^{-\beta \, Ed / Ps}$ (Platt *et al.* 1981)

where P_s (mg C mg Chl a^{-1} m^{-3} h^{-1}) is the light saturated rate of photosynthesis in the absence of photo-inhibition, α (mg C mg Chl a^{-1} m^{-3} h^{-1} μmol m^{-2} s^{-1}) is the initial slope of the P^b-E_d curve, and β (mg C mg Chl a^{-1} m^{-3} h^{-1} umol m^{-2} s^{-1}) is the photoinibition effect due to high irradiance. Parameter estimates were determined using the Levenberg-Marquardt algorithm (Kalediagraph v3.5, 1998). The photo-inhibition response (β) was apparent in all the curves with the exception of June sampling dates where β values were low.

We measured daily primary production rates at 10m from the photosynthesis-irradiance experiments and estimated integrated primary production within the euphotic zone using data on daylength, chlorophyll *a* and irradiance (PAR) profile data at depths extending to the euphotic zone. (Figure 9). The general trend in primary production increased from relatively low levels during summer to higher levels through the Fall period. Integrated primary production ranged from ca. 50 to 500 mg C m^{-2} d^{-1} and maximal levels were observed in early Fall 2000 at Station 27. Recent production data collected during Jan.-Feb. 2001 at Station 27 show rates similar to those observed during Summer 2000 (Figure 9).

TRANSECTS-IRRADIANCE

Irradiance data was collected during transect survey's using a quantum PAR irradiance sensor (Biospherical QSP-200PD) attached to a Seabird SBE-911 profiling CTD. Estimates of the attenuation coefficient (see above) were used to estimate the euphotic depth, at which lights reaches 1% of the surface irradiance value.

In the Spring of 2000, there was marked gradient in euphotic depth from the southeast Grand Banks onto the Newfoundland shelf (Figure 10a). Along the Bonavista and Flemish Cap transects, the euphotic depth was well above 50m, whereas along the southeast Shoal transect, the euphotic depth was generally in excess of 50m. Patterns of euphotic depth tend to be inversely related to the total phytoplankton biomass. During the Summer of 2000, euphotic depths were often in excess of 75m, indicative of low levels of phytoplankton biomass. Areas with strong currents tended to have deeper euphotic zones than shallower areas (Figure 10b). Only on Hamilton Bank was the euphotic depth consistently above 75m. In the Fall of 2000, euphotic depth varied between 50 and 100 m (Figure 10c). There is some evidence of a deeper euphotic zone in areas close to shore than on the Newfoundland shelf or out toward the shelf break.

TRANSECTS – NUTRIENTS

By late April-early May, nitrate and silicate concentrations in the upper 50m over the Grand Banks are generally < 1μM, while concentrations are still not fully depleted by the spring bloom along the Bonavista transect (Figure 11). Over the continental slope and on the Flemish Cap, where the Labrador current is stronger, nutrient levels suggest that the spring phytoplankton bloom is still on-going.

In late July-early August, nitrate and silicate concentrations on the Grand banks remain depleted in the surface layer but as one moves further north, the depth of the nutricline decreases and nutrient concentrations of 2 µM can often be found near the surface (Figure 12). Furthermore, there appears to the an increase in the concentrations of nitrate and silicate at depths below the nutricline relative to the spring surveys along the Bonavista and Flemish Cap transects.

Surface layers were still depleted in nitrate and silicate in early November (Figure 13), although there was some indication of mixing along the Bonavista transect, which was not apparent on any of the transects crossing the Grand Banks. At a depth of ~150m, concentrations of silicate appear to be higher than in the spring across the entire continental shelf and slope whereas nitrate concentrations appear to be higher only in areas where the Labrador current is more intense (e.g. Bonavista transect, Flemish Pass, Avalon Channel) (Figure 13). The increase in both deep silicate and nitrate appears to be ~ 2µM, similar to that observed at Station 27.

The concentration of nitrate versus silicate during 1999-2000 surveys indicated the uptake of silicate by diatoms was also important during all seasons, but utilization rates were typically lower compared to Station 27, particularly during 2000 in contrast to 1999 where the rates were similar (Figure 4). The intercepts indicated that nitrate is the limiting macronutrient to phytoplankton growth on the Newfoundland and Labrador Shelf.

TRANSECTS-CHLOROPHYLL / PHYTOPLANKTON

Three transect surveys were completed during Spring, Summer, and Fall 2000. Phytoplankton biomass levels estimated from chlorophyll *a* were generally > 100 mg m^{-2} during the Spring survey except for several stations on the southeast Grand Banks and Bonavista lines where levels were below 50 mg m^{-2} (Figure 14d). The relatively high phytoplankton biomass levels observed during the Spring survey were consistent with the general timing and magnitude of the bloom at station 27 (Figure 5a). Comparison with 1999 results is limited due to the cancellation of the Spring cruise. Observation of phytoplankton biomass on the Bonavista transect in Spring 1999 indicate that levels were < 100 mg m^{-2} compared to higher levels observed during 2000 (Figure 14a). Phytoplankton biomass levels observed during the Summer survey were typically low (< 50 mg m^{-2}) across the northern Grand Banks and northeast shelf region but rapidly increased on the Labrador shelf and slope waters (Figure 14e). Again we observed increases in biomass across the slope waters coincident with the transition into the Labrador current. The magnitude and spatial patterns were similar between 1999 and 2000 showing low biomass levels across the northern Grand Banks and northeast shelf regions while levels on the Labrador shelf and slope were elevated (Figure 14b). No evidence of extensive blooms were observed during the Fall 2000 survey (Figure 14f). Phytoplankton biomass was generally < 50 mg m^{-2} and a large number of stations on the southeast Grand Banks and Flemish Cap lines showed values < 25 mg m^{-2}. The magnitude and spatial patterns were different between years in that biomass levels were greater in 1999 compared to 2000. The interpretation of interannual differences requires some caution due to variation in timing of surveys and production dynamics.

Vertical profiles of chlorophyll *a* observed during the Spring 2000 survey indicated extensive regions of phytoplankton blooms and offshore gradients (Figure 15). Concentrations of chlorophyll *a* along the northeast Newfoundland shelf and slope waters reached values > 10 mg

m^{-3} in the upper 50m and a deep chlorophyll maximum at 50m was evident on the northern edge of the Grand Banks along the Station 27 transect (Figure 15 a, b). Concentrations on the Flemish Cap and southeast Grand Bank transect lines were also elevated on the bank and slope regions (Figure 15 c, d). Sinking of the phytoplankton bloom was observed in the near-shore and on bank regions of the southernmost transects, consistent with the patterns observed at Station 27 at this time (Figure 5a). Profiles of chlorophyll *a* observed during the Summer survey indicated extensive subsurface blooms (chlorophyll *a* > 10 mg m^{-3}) along the Labrador shelf, and deeper, localized concentrations along the northeast Newfoundland shelf and northern Grand Banks (Figure 16). Observation of a deep chlorophyll maximum along Makkovik and Beachy Island transects indicate progression of blooms from coastal to offshore regions, consistent with the spatial patterns observed for the Spring survey (Figure 16 a, b). Concentrations of chlorophyll *a* along the northeast Newfoundland shelf and slope waters were generally low (< 1 mg m^{-3}), except for localized deep chlorophyll maxima (Figure 16d-g). Profiles of chlorophyll *a* observed during the Fall survey indicated both widespread increase in surface concentrations, typically < 3 mg m^{-3}, relative to levels observed during the Summer (Figure 17a-c). Concentrations of chlorophyll along the southeast Grand Banks were below 1 mg m^{-3} except for a deep chlorophyll maximum located at the shelf break (Figure 17d).

Cell densities of the major taxonomic phytoplankton groups found in 2000 exhibited a pattern to that observed in 1999 (Figure 18). Diatoms showed the greater seasonal pattern of variation, with spring concentrations ~100-300 times that found during the remainder of the year. As in 1999, there was evidence of a slight increase in diatom concentrations during the fall cruise, which is somewhat in contrast to observations at Station 27. Concentrations of dinoflagellates showed little seasonality and were generally higher than those of diatoms, except during the Spring survey. As in 1999, flagellates were at least 10 times more abundant than dinoflagellates and there was an overall trend of increasing concentrations from Spring to Fall, which was not evident during 1999.

ZOOPLANKTON – FIXED STATION

Total zooplankton abundance in 2000 was higher than levels observed in 1999 and on par with the highest of observations observed during the 1996-99 period (Figure 19a). During the months of February through April, more of the biomass was contained in the size fraction below 1000 µm but after that, the biomass was more equally distributed in fraction > and < 1000 µm (Fig. 19b). The zooplankton community was dominated by small copepodite stages of *Oithona similis* and *Pseudocalanus* sp. throughout the year. The abundance of large calanoid nauplii and larvaceans increased substantially following the spring phytoplankton bloom (March-April). It is difficult to identify any substantial shift in species composition relative to previous observations (Figure 19d). Shannon's Entropy Index ($H = -S\, p_i \ln p_i$, where p_i is the proportion of species i in a sample of N species) recorded in 2000 was well within the range of previous observations (1993-99) (Figure 20a) and seasonal cycle in the ratio of large-to-small copepods (all *Calanus* species + *Metridia longa* versus all other species of copepods) was not substantially different from previous observations, although levels appeared to be low in May-June (Figure 20b).

Dominant species, such a *O. similis* and *Pseudocalanus* sp. were within the higher range of previously observed abundance levels (Figure 21). The abundance of the dominant large species

(C. finmarchicus and C. glacialis) was approximately equal to that observed in 1999. Less dominant species, such as *Microcalanus* sp. and *Oikopleura* sp. were within the range of previous observation, while *Temora longicornis* was found at relatively low levels in contrast with previous data from Station 27.

As with the overall abundance of *Calanus* sp., the abundance of calanoid nauplii caught by the 202 µm mesh net was in the range of the higher levels previously recorded, but the densities tended to be even closer to the extremes of the range (Figure 22). It appears that in 2000, the seasonal abundance pattern of large calanoid nauplii occurred over a more protracted period than in 1999. Stallard (1988) suggested that nauplii > 200 µm carapace width found in coastal Newfounland were likely to consist of stage II+ *C. finmarchicus* and Stage I+ *C. glacialis*. When viewed relative to the abundance of adult females (*C. finmarchicus* + *C. glacialis*), the production of large calanoid nauplii in 2000 was generally higher than levels observed in 1999 (Figure 22). This is in contrast with observations of total nauplii abundance, measured from 70 µm mesh net samples, which showed that the overall abundance of nauplii at Station 27 was comparable to previous observations (Figure 23).

Although observations of the seasonal development of copepodites of *C. finm*archicus and Pseudocalanus sp. have been limited in the past (due partly to issues of data quality), the pattern of seasonal development in 2000 does not show evidence of any substantive change in seasonality for either species during the first half of the year (Figure 24).

ZOOPLANKTON – TRANSECTS

The overall abundance of zooplankton (m^{-2}) during each of the spring and summer cruises of 2000 did not appear to be substantially different from the observations in the previous year (Figure 25) and the same could be said for the general pattern of abundance of the major taxonomic groups (e.g. *O. similis*, *Pseudocalanus* sp., *C. finmarchicus* and *C. glacialis*). As in previous years, most of the dominant taxa were widespread across the entire shelf. *O. similis* is most abundant species throughout the region but it dominates on the Grand Banks. *Pseudocalanus* sp. decreases in abundance as one moves away from the coast and *C. finmarchicus* is abundant across the entire shelf but it is relatively scarce on the Grand Banks (Figure 26).

Species composition during the summer cruise was not substantially different in 2000 relative to previous years (1996-1999). The overall pattern of species diversity in 2000 relative to previous years was similar to the pattern observed at Station 27, with values being neither high nor low. A canonical discriminant analysis, similar to that presented by Pepin and Maillet (2000), revealed three major clusters of species, each one dominated by one of the three major species groups (*Pseudocalanus* sp., *C. finmarchicus, O. similis*) (Table 2). The only notable difference in 2000 relative to the summer 1999 was an apparent cross shelf expansion of the cluster dominated by *Pseudocalanus* sp. along the coast of Labrador and a greater restriction to the Grand Banks of the community heavily dominated by O. similis (Figure 27).

There was s strong north-to-south gradient in the stage composition of *C. finmarchicus* during the spring survey of 2000 (April-May). Adult stages dominated the population along the

Bonavista Bay transect, with relatively fewer numbers being found along the Flemish Cap line and almost none on the Southeast Shoal (Figure 28). When contrasted with previous years, this appears to suggest that the C. finmarchicus population is somewhat delayed because of the smaller fraction of earlier copepodites stages. However, during the remainder of the year (Figure 28) there appears to be no notable differences in the distribution of copepodite developmental stages along the major transects of the shelf. Subtle differences in the timing of the spring surveys may caused perceived changes in the distribution of developmental stages even though the seasonal progression of development is unchanged. A similar pattern of development was also noted for *Pseudocalanus* sp. but the difference in the distribution of development stages during the spring survey of 2000 relative to previous years was not as notable as for *C. finmarchicus* (Figure 29).

The most notable difference between years was in the abundance of large calanoid nauplii, relative to the number of adult *C. finmarchicus* and *C. glacialis*, from the 202 µm mesh samples (Figure 30). During the summer of summers of 1999 and 2000, the abundance adult C VI *C. finmarchicus* and *C. glacialis* was similar. However, the abundance of large calanoid nauplii found in 2000 was approximately twice that of observed in 1999 (Figure 31), a pattern which is consistent with our observations at Station 27. At stations where adults and nauplii co-occurred, the number of nauplii per adult in 2000 was approximately 3 times the level found in 1999. Although adult *Calanus* sp. were not found on the Grand Banks, based on our sampling of the Flemish Cap transect, large number of nauplii were observed, suggesting that transport may play an important role in populating the Grand Banks with *Calanus* nauplii and copepodites.

DISCUSSION

The contrast in chemical and biological conditions on the Newfoundland Shelf in 2000 relative to observations from 1999 was generally limited in magnitude but there were some notable differences. The significance of those changes to the ecosystem are still difficult to establish given that our understanding of the dynamic interactions must acknowledge some important gaps.

Overall, patterns of variations between 1999 and 2000 in the standard variables measured at the fixed station (Station 27) were generally consistent with the regional observations collected during the oceanographic surveys. However, there were some notable discrepancies as well.

Depth of the euphotic layer (1% light level) followed a seasonal cycle that was consistent with expectations based on the seasonal development of the phytoplankton community. Following the spring bloom when the high biomass of phytoplankton severely limits light penetration, the euphotic depth at Station 27 fluctuated slightly around a depth of 60m during the course of the summer and into the late fall, consistent with the relatively constant levels of phytoplankton biomass. A similar pattern was also observed over the shelf, where the depth of the euphotic layer fluctuated between 50-100m, depending on local conditions.

The overall levels of inorganic nutrients were generally similar to those observed in 1999. Depletion of nitrate and silicate in the upper water column appears to have been deeper in 1999 than in 2000, suggesting that mixing may have been more limited during the latter year. This was consistent both at Station 27 and during our oceanographic surveys. One notable difference from 1999 was an apparent influx of higher concentrations of nitrate and silicate during late Fall. These waters with slightly higher (~2µM) concentrations of inorganic nutrients were only found in the deep near bottom waters associated with the Labrador current. As such, the increased levels of nutrients were only apparent on the Newfoundland Shelf, the water of the continental slope and the Avalon Channel.

The seasonal phytoplankton production cycle in 2000 differed substantially from the observations from 1999. In contrast to 1999, the spring phytoplankton bloom was restricted to the upper 60m of the water column whereas it was distributed over a greater depth interval in 1999. The chlorophyll maximum in 2000 was also less dynamic than in 1999 when we had observed a number of small subsurface blooms. Overall the subsurface chlorophyll concentration in 2000 was approximately one half to one third of that observed in 1999. Similar differences in the vertical distribution of phytoplankton biomass were also observed during the three oceanographic surveys. In addition, our Fall survey found little evidence of a Fall bloom on the southern Grand Banks, a feature noted in 1999.

The overall abundance of zooplankton in 2000 was among the higher levels observed since 1996. The increase appears to have been due largely to increases in the overall abundance of *Oithona similis* and *Pseudocalanus* sp. copepodites, the numerically dominant species found on the shelf. This pattern was not evident during our summer survey, when the overall abundance of zooplankton in 2000 was approximately equal to that observed in 1999. The abundance and seasonal progression of copepodites stages of *Calanus finmarchicus* and *C. glacialis* was of the same order as in the previous year, as was the abundance of larvaceans, pelagic gastropods, and the less dominant species of copepods. Species diversity as well as the relative abundance of large and small copepods was similar to that previously observed. The distribution of zooplankton communities during the Summer oceanographic survey indicates a slight increase in the spatial extent of the two communities dominated by *O. similis* and *Pseudocalanus* sp., suggesting the possibility of a competitive balance between the two species.

The most notable difference between 1999 and 2000 was in the overall abundance of large calanoid nauplii, likely contributions from both *C. finmarchicus* and *C. glacialis*. Overall abundance levels observed at Station 27 as well as during the Summer oceanographic survey were approximately twice that observed in 1999. It was more difficult to contrast the Spring surveys as their timing differed between years and the production of nauplii shows a very rapid increase associated with the Spring phytoplankton bloom. Since the abundance of adult copepodites (CVI) was not substantially different in 1999 and 2000, our observations suggest there was an increased reproductive rate during the last year which persisted throughout the productive season (April-November). There is also a suggestion of a more rapid development or better survival from early to late copepodite stages of *C. finmarchicus* during the latter part of the Summer but the data are currently insufficient to confirm this pattern.

If there was an increase in secondary production during 2000 relative to the previous year, this may partly account for the lower overall levels in subsurface phytoplankton biomass observed across the shelf.

ACKNOWLEDGEMENTS

We thank Dan Lane, Sandy Fraser, and Julie Rumsey for their steadfast work on this project. The expertise of Gerhard Pohle, Cynthia MacKenzie, Chris Parrish, Mary Greenlaw and Janette Wells was crucial for the completion of this work.

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Table 1. Listing of surveys, dates and transects for 2000. The transects are: southern Grand Banks (SEGB); Flemish Cap (FC); Station 27 line (S27), Bonavista Bay (BB); Funk Island (FI); White Bay (WB); Seal Island (SI); Makkovik Bank (MB); and Beachy Island (BI) (See Figure 1.).

Year	Day	Transects
2000	113-128 (spring)	SEGB, FC, S27, BB
2000	196-212 (summer)	FC, BB, FI, WB, SI, MB, BI
2000	306-315 (fall)	SEGB, FC, S27, BB

Table 2. Cluster mean relative abundance of zooplankton as determined from a canonical discriminant analysis of the transect data from 1996-2000.

Taxon	Cluster 1 (Coastal)	Cluster 2 (N. Shelf)	Cluster 3 (GB)
Pseudocalanus sp.	0.33	0.066	0.079
Acartia sp.	0.0026	0.0007	0.0016
Balanus sp.	0.0007	0.0002	0.0002
Calanus finmarchicus	0.088	0.33	0.079
other *Calanus* species	0.066	0.045	0.017
Oithona similis	0.37	0.40	0.69
Centropages hamatus	0.012	0.0036	0.011
Temora longicornis	0.015	0.0002	0.011
Aglantha digitale	0.0006	0.0007	0.0016
Paracalanus sp.	0.0013	0.0002	0.0028
Euphausiids	0.0013	0.01	0.004
Metridia sp.	0.0074	0.027	0.0063
Sagitta sp.	0.0026	0.0079	0.0036
Oikopleura sp.	0.050	0.041	0.044

Figure 1. Station locations during spring (a), summer (b), and fall (c) 2000 surveys on the Newfoundland and Labrador Shelf. Detailed sampling (CTD, phyto- and zooplankton, chl a, and nutrients) stations indicated by (open circle) symbol, CTD-only by +, and the fixed station by a closed circle. Contour lines are 200 and 1000m isobaths. Transect lines include southeast Grand banks (SEGB), Flemish Cap (FC), Station 27 (S27), Bonavista Bay (BB), Funk Island (FI), White Bay (WB), Seal Island (SI), Makkovik Bank (MB), and Beachy Island (BI).

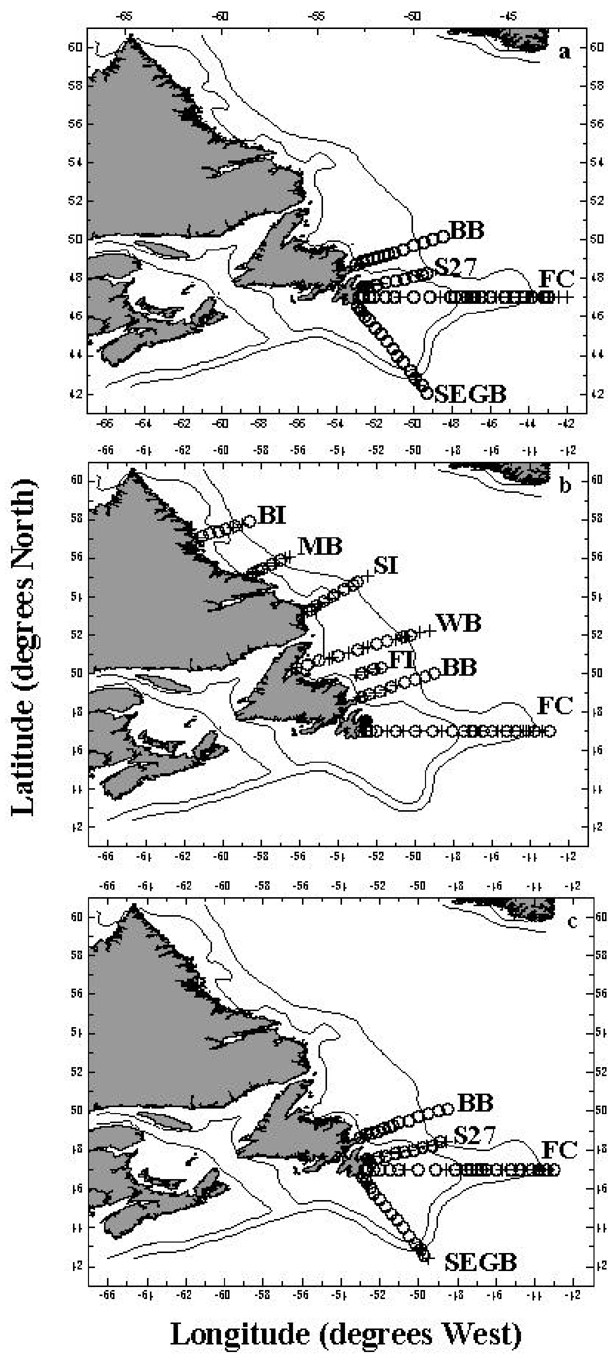

Figure 2. Station 27 time series of (a) vertical attenuation coefficient (K_{d_PAR}) estimated from PAR (photosynthetic active radiation; 400-720 nm), Secchi disk depth, and chlorophyll a biomass, (b), phytoplankton cell density and integrated chlorophyll a over two depth strata, (c) stratification index (density 50m - density (surface) / 50m) and mixed layer depth (depth centre of pychnocline), (d) estimated euphotic (Z_{eu}) depth based on K_{d_PAR} and chlorophyll a biomass during 2000.

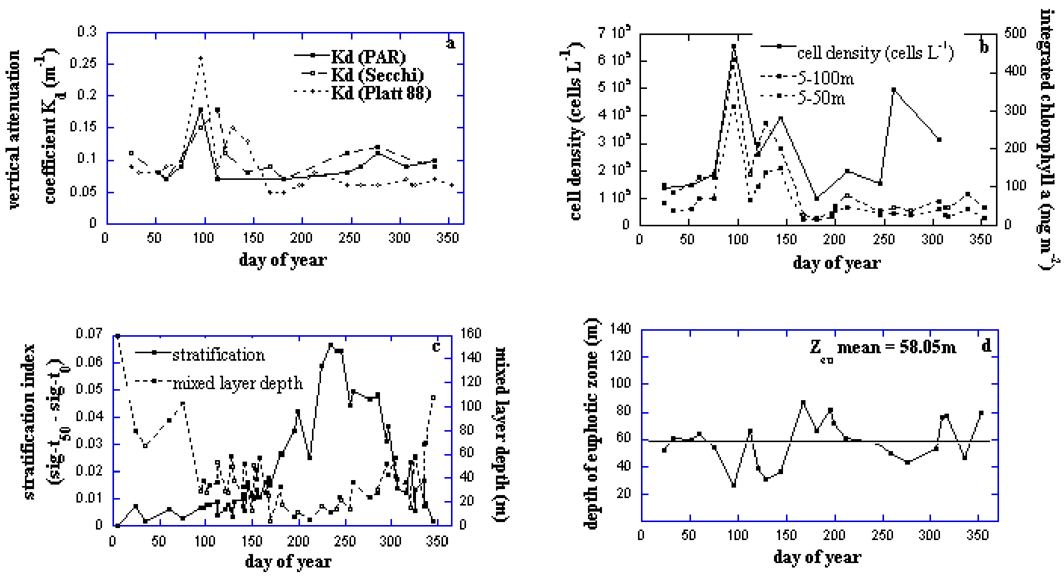

Figure 3. Vertical profiles of nitrate (top panels), phosphate (middle panels), and silicate (bottom panels) concentrations (μM) versus day of year. Left panels (a-c) are 1999 data, right panels (d-f) are 2000 data. White overlay panels indicate large data gaps. Sample locations on contour plot shown as small open circles.

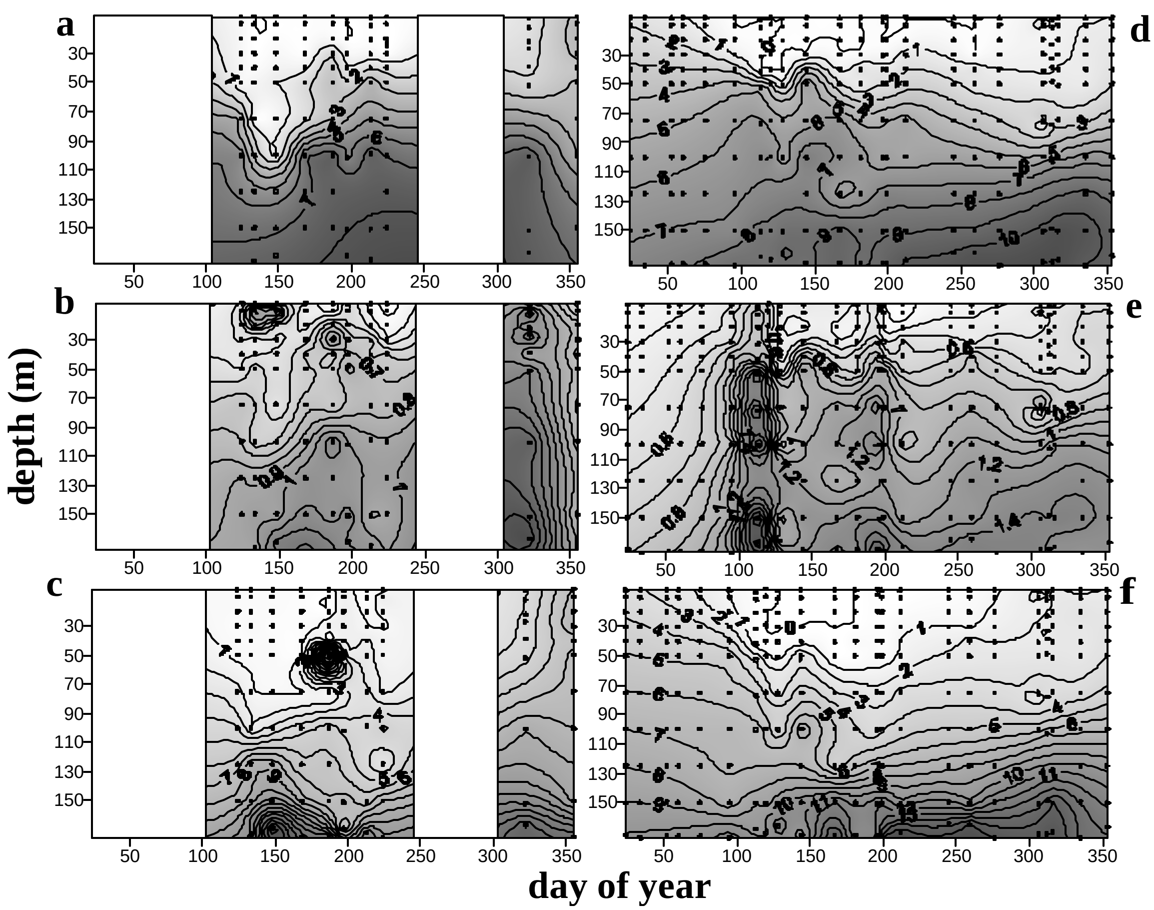

Figure 4. Relationship between silicate and total nitrate (nitrate + nitrite) for transect station occupations and Station 27 during 1999 and 2000. Linear regression statistics provided for transect and fixed station. Asterisks indicate intercept significantly different from zero (P < 0.05), while NS indicates not significant.

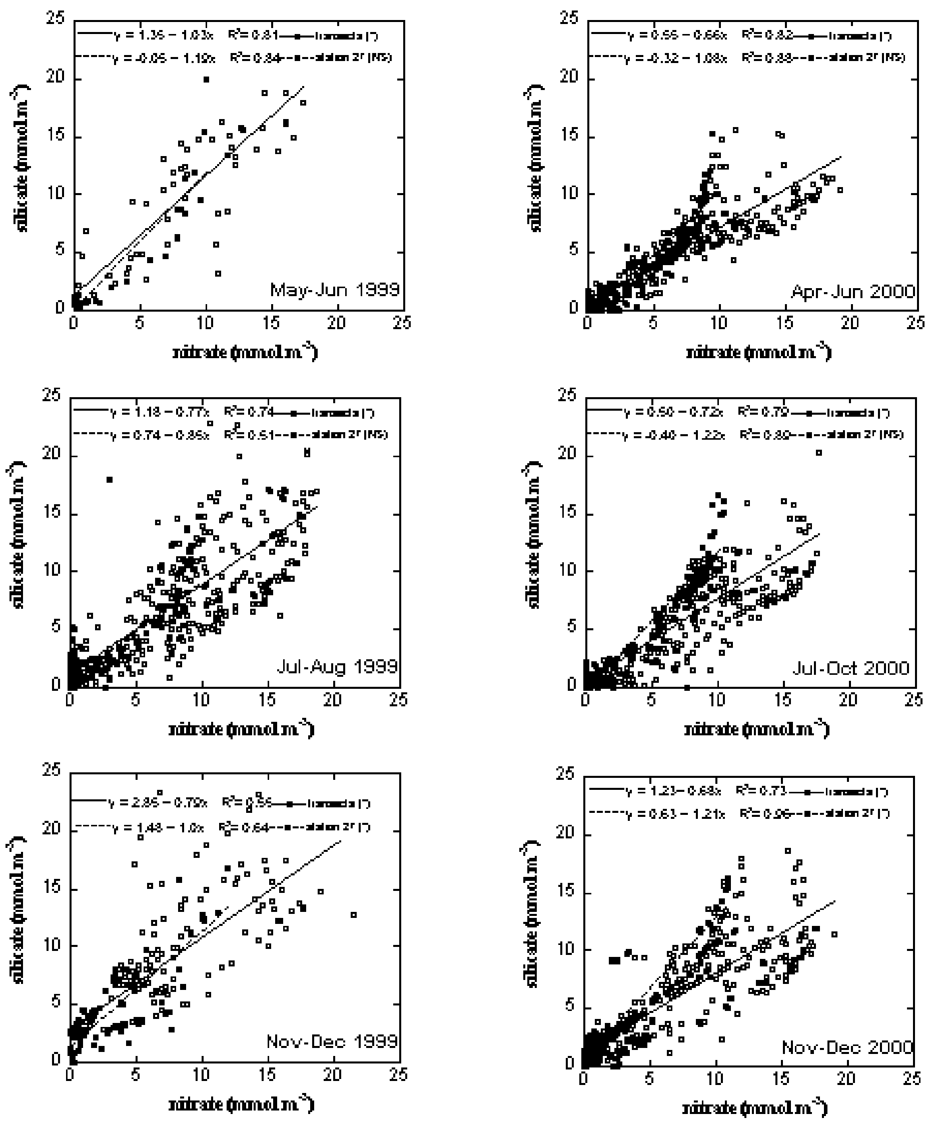

Figure 5. Vertical profiles of chlorophyll a versus day of year at Station 27. Data for (a) 2000, and (b) 1999 period. White overlay panels indicate large data gaps. Sample locations are shown as small open circles.

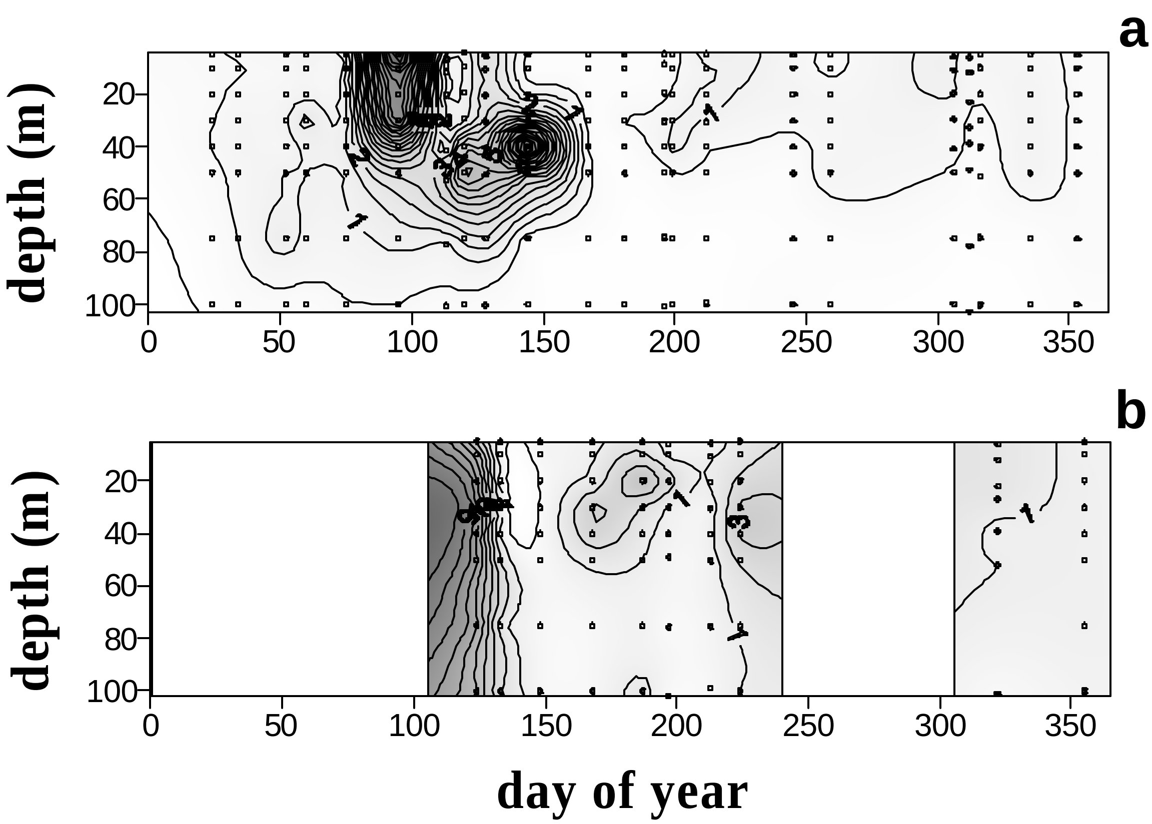

Figure 6. Time series of estimated parameters derived from Gaussian model fit to both fluorescence profile and discrete chlorophyll a values obtained from Station 27 during year 2000. Parameters; (a) background fluorescence and chlorophyll a concentration, (b) total fluorescence and chlorophyll a biomass above background, (c) standard deviation of fluorescence and chlorophyll a biomass, and (d) depth of fluorescence and chlorophyll a maximum.

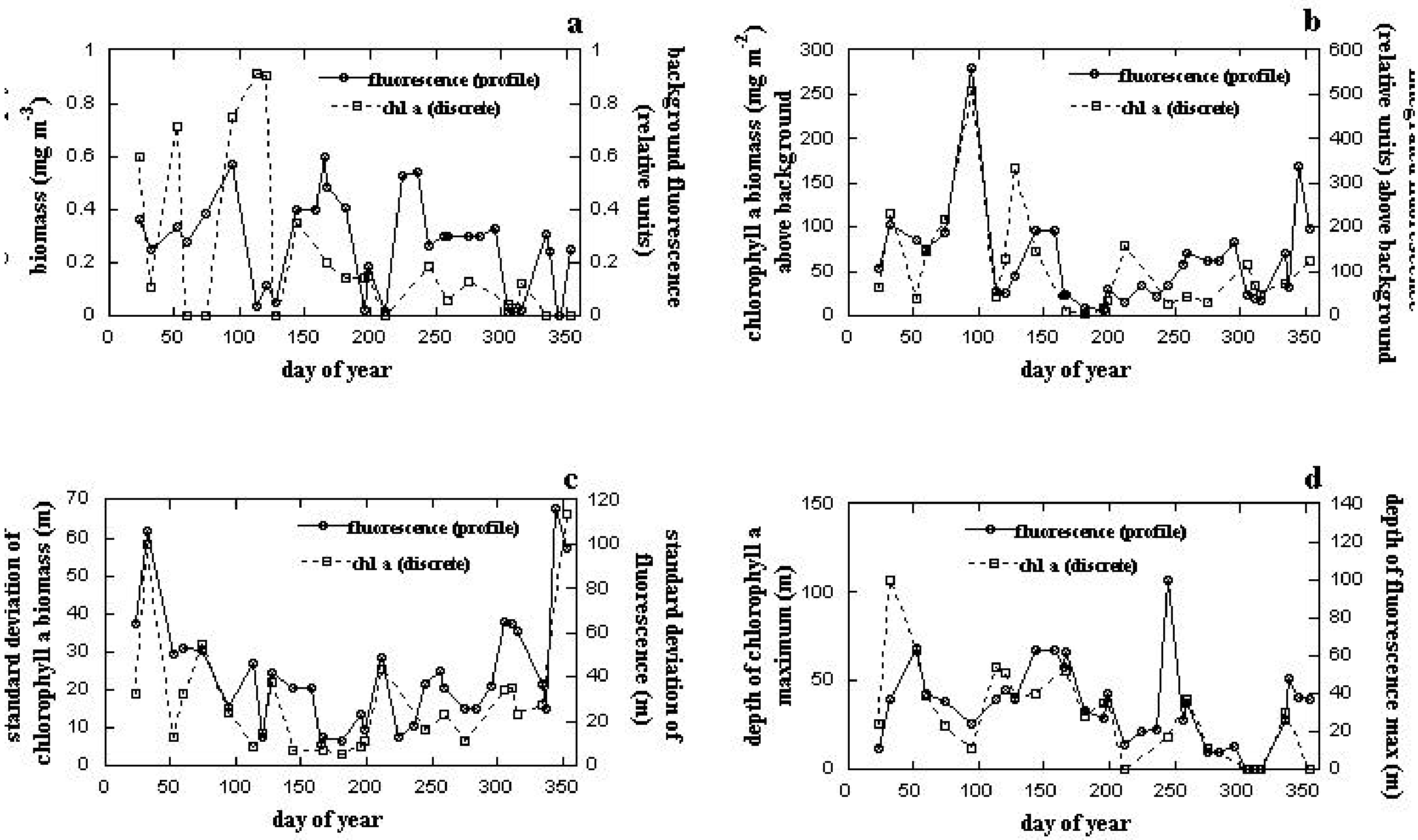

Figure 7. Monthly variation in cell density and the relative abundance of major phytoplankton taxa observed at Station 27 during 2000 including (a) diatoms, (b) dinoflagellates, (c) flagellates, and (d) major phytoplankton group ratios.

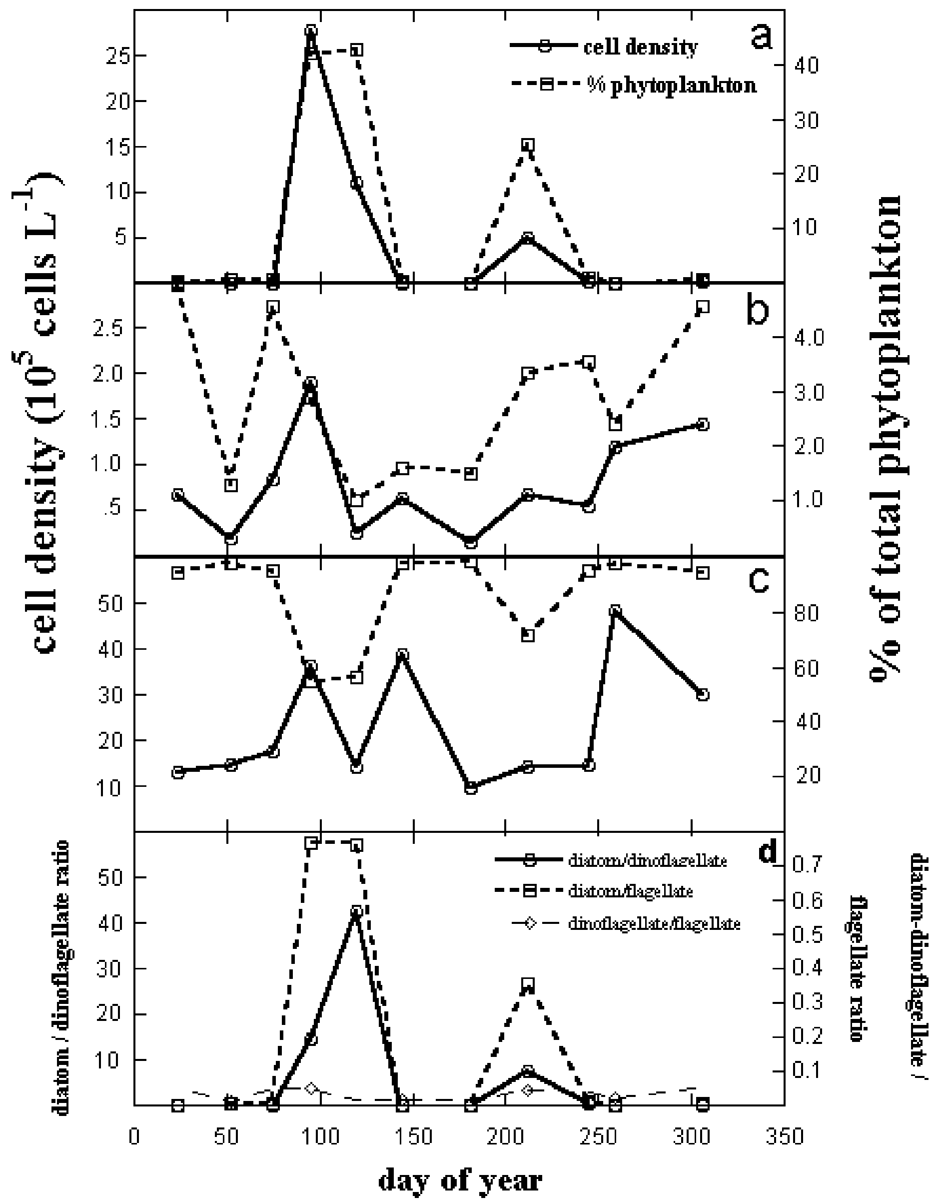

Figure 8. Monthly variation in cell density and the relative abundance of major taxonomic groups of flagellates observed at Station 27 during 2000 including (a) Cryptophytes, (b) Chrysophytes, (c) Dictyophytes, (d) Prymnesiophytes, (e) Euglenophytes, (f) Prasinophytes, (g) Chlorophytes, (h) Choanoflagellates, and (i) unidentified biflagellates.

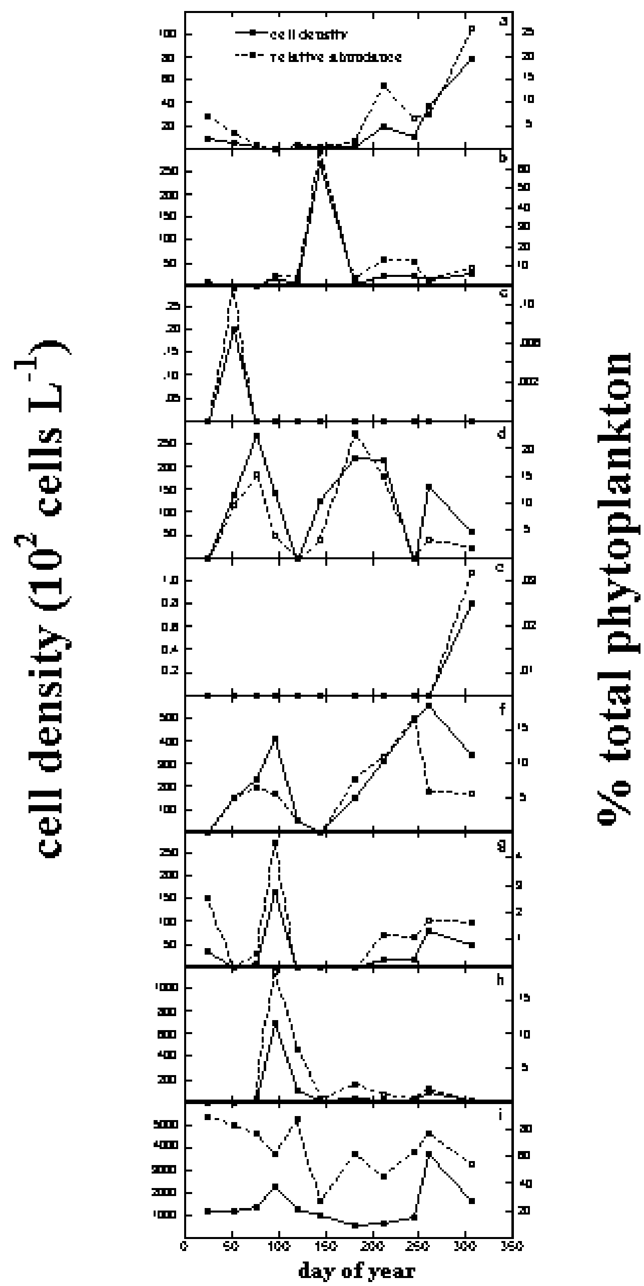

Figure 9. Observed daily primary production at 10m depth and estimated integrated daily primary production over the euphotic zone from Station 27 based on photosynthesis- irradiance curves, chlorophyll a and irradiance (PAR) profiles during 2000-01 period.

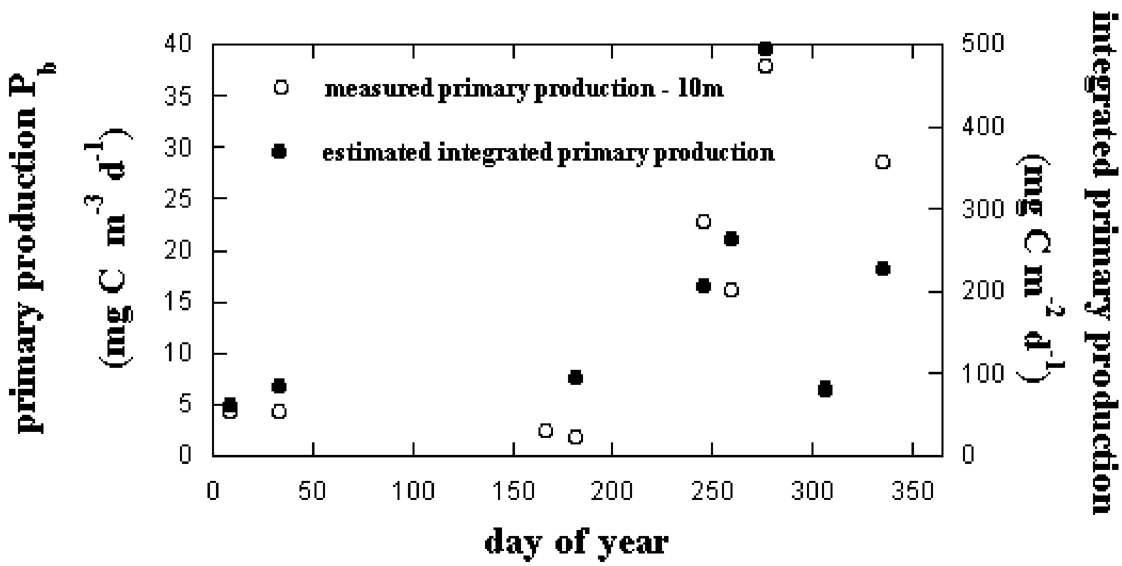

Figure 10. Distribution of estimated euphotic depth (m) across transect lines during (a) Spring, (b) Summer, and (c) Fall 2000 surveys. Transect lines include southeast Grand Banks (SEGB), Flemish Cap (FC), Bonavista Bay (BB), White Bay (WB), Seal Island (SI), and Station 27 (S27).

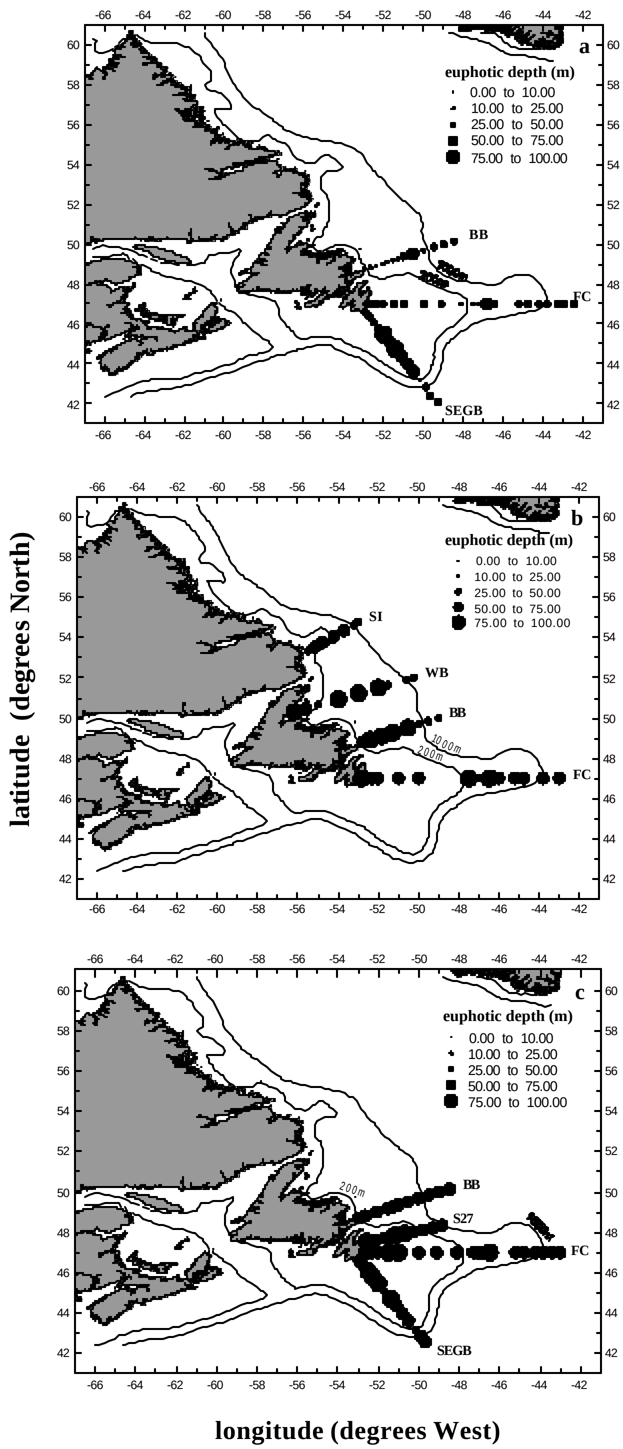

Figure 11. The Spring 2000 concentrations of silicate (left panels) and nitrate (right panels) in micro-moles (uM) versus depth along transects across (a,b) Bonavista Bay, (c,d) Station 27 line, (e,f) Flemish Cap, and (g,h) southeast Grand Banks. Bottom bathymetry shown in solid black. Sample locations on contour plots shown by small open circles.

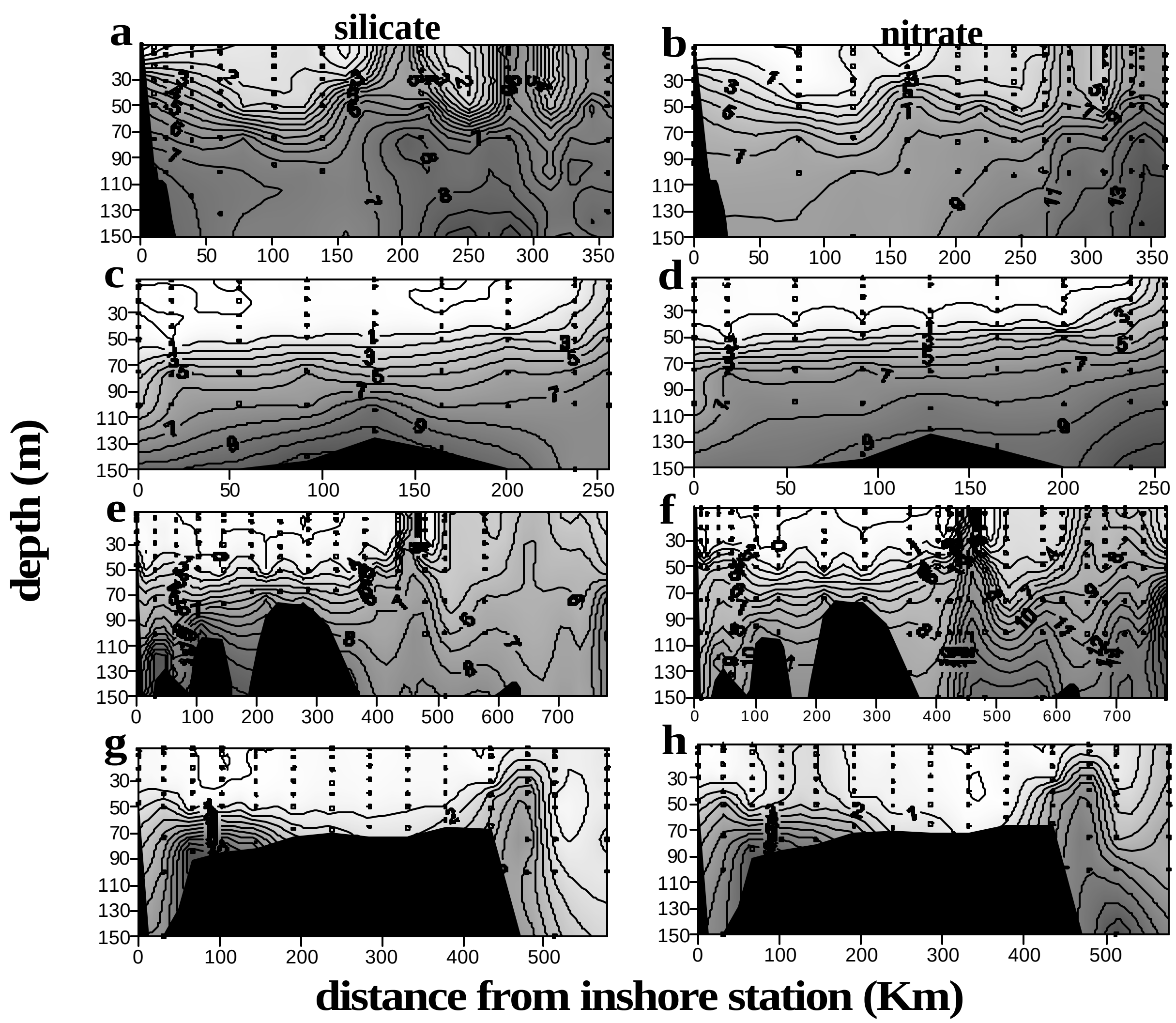

Figure 12. The Summer 2000 concentrations of silicate (left panels) and nitrate (right panels) in micro-moles (uM) versus depth along transects across (a,b) Seal Island, (c,d) White Bay, (e,f) Bonavista Bay, and (g,h) Flemish Cap. Bottom bathymetry shown in solid black. Sample locations on contour plots shown by open circles.

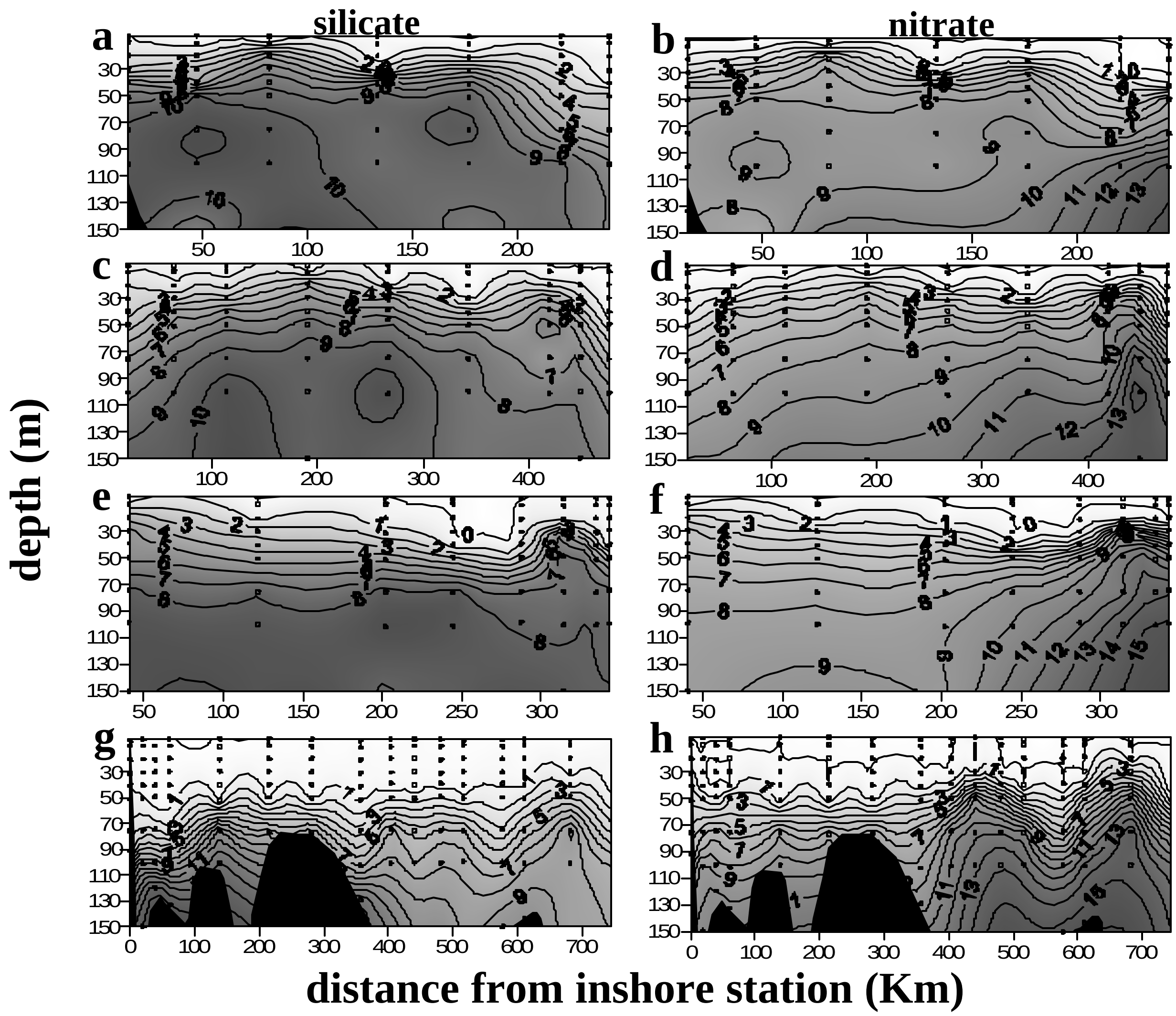

Figure 13. The Fall 2000 concentrations of silicate (left panels) and nitrate (right panels) in micro-moles (uM) versus depth along transects across (a,b) Bonavista Bay, (c,d) Station 27 line, (e,f) Flemish Cap, and (g,h) southeast Grand Banks. Bottom bathymetry shown in solid black. Sample locations on contour plots shown by open circles.

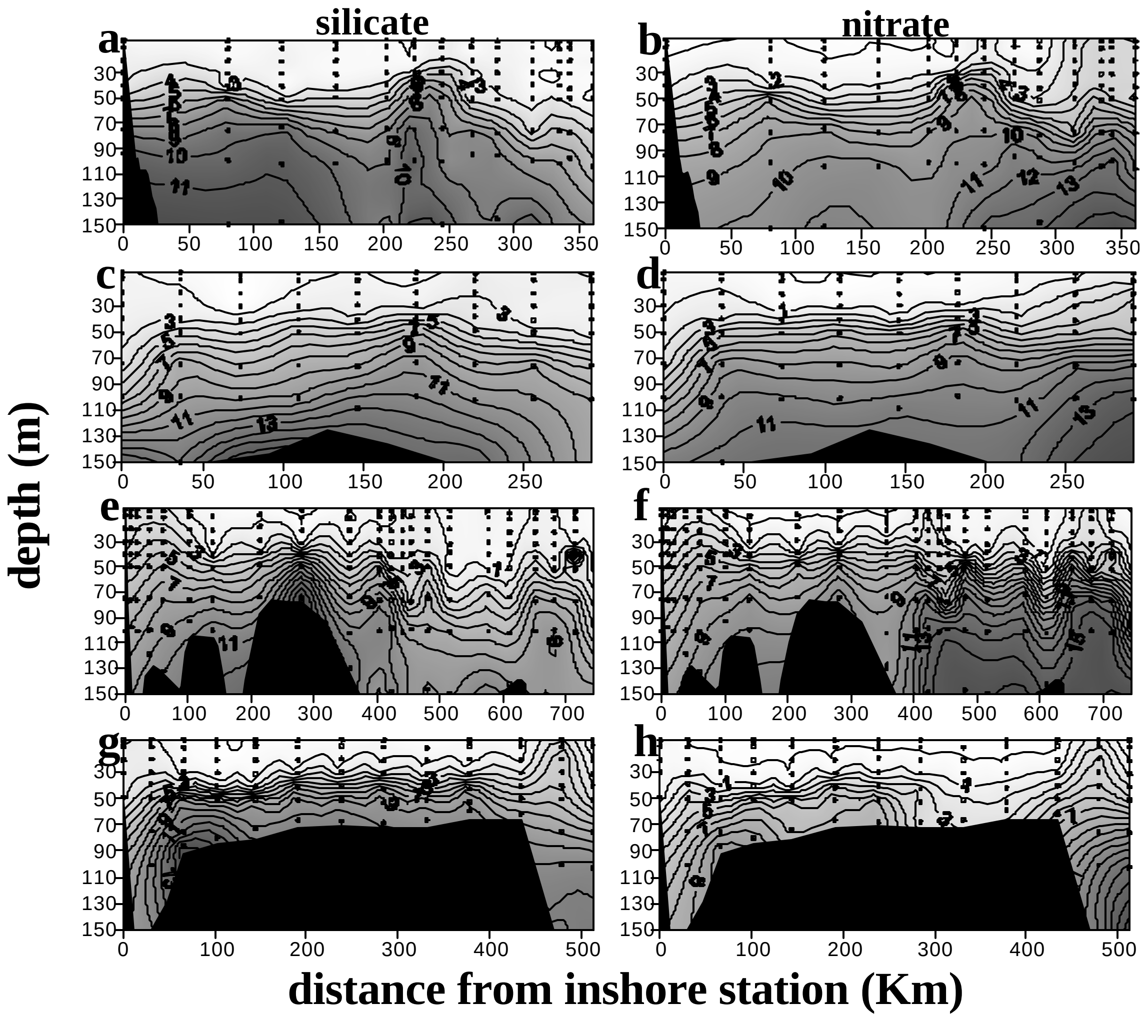

Figure 14. Distribution of phytoplankton biomass across transect lines during 1999-2000. Left panels (a-c) show 1999 data for (a) Spring, (b) Summer, and (c) Fall periods. Right panels (d-f) show 2000 data for corresponding seasonal periods. Transect lines include southeast Grand Banks (SEGB), Flemish Cap (FC), Station 27 (S27), Bonavista Bay (BB), Funk Island (FI), White Bay (WB), Seal Island (SI), Makkovik Bank (MB), Nain Bank (NB), and Beachy Island (BI).

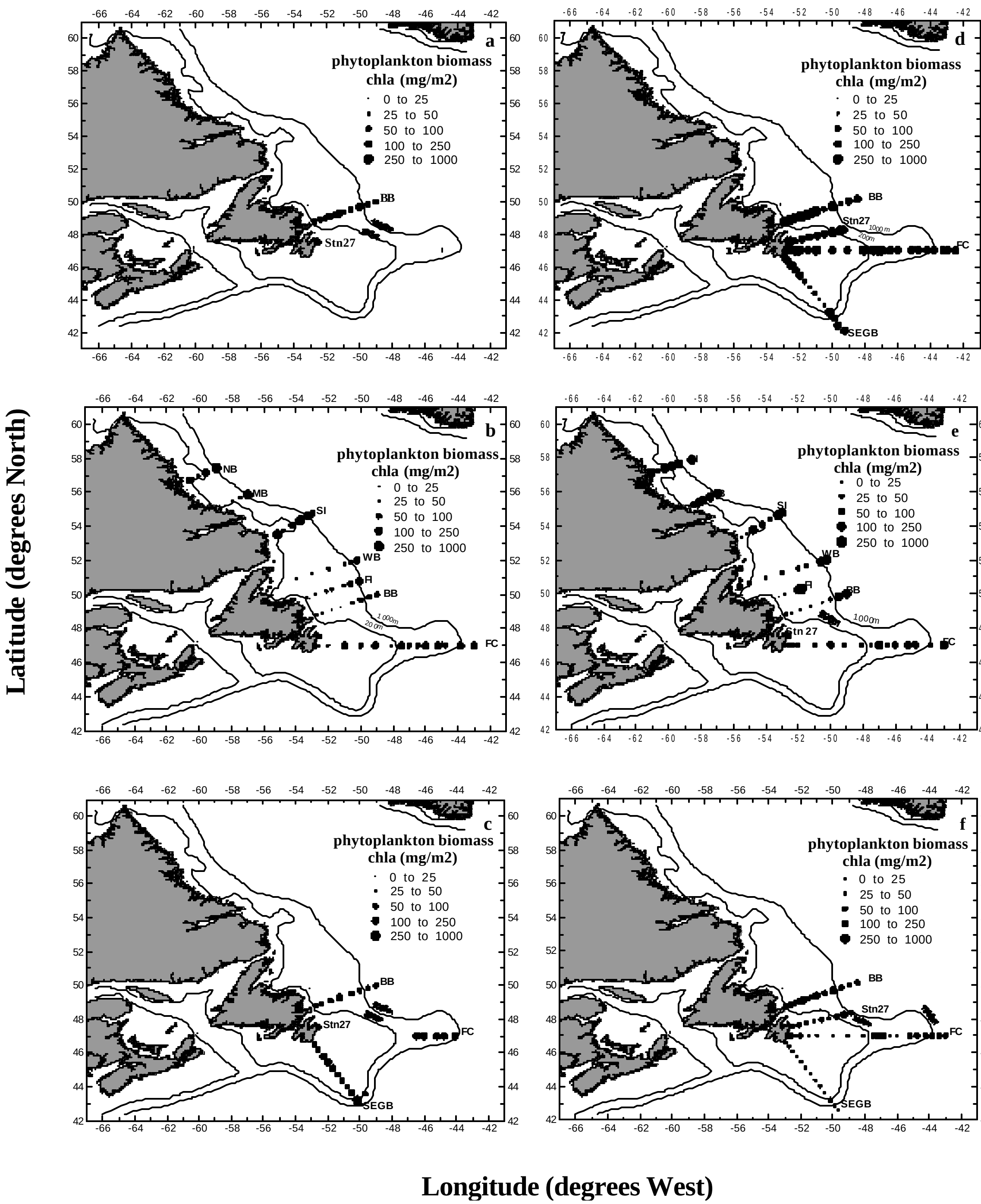

Figure 15. Vertical profiles of chlorophyll a versus distance from the inshore station during Spring 2000 surveys across (a) Bonavista Bay, (b) station 27 line, (c) Flemish Cap, and (d) southeast Grand Banks transects. Bottom bathymetry shown in solid black. Sample locations on contour plots shown by small open circles.

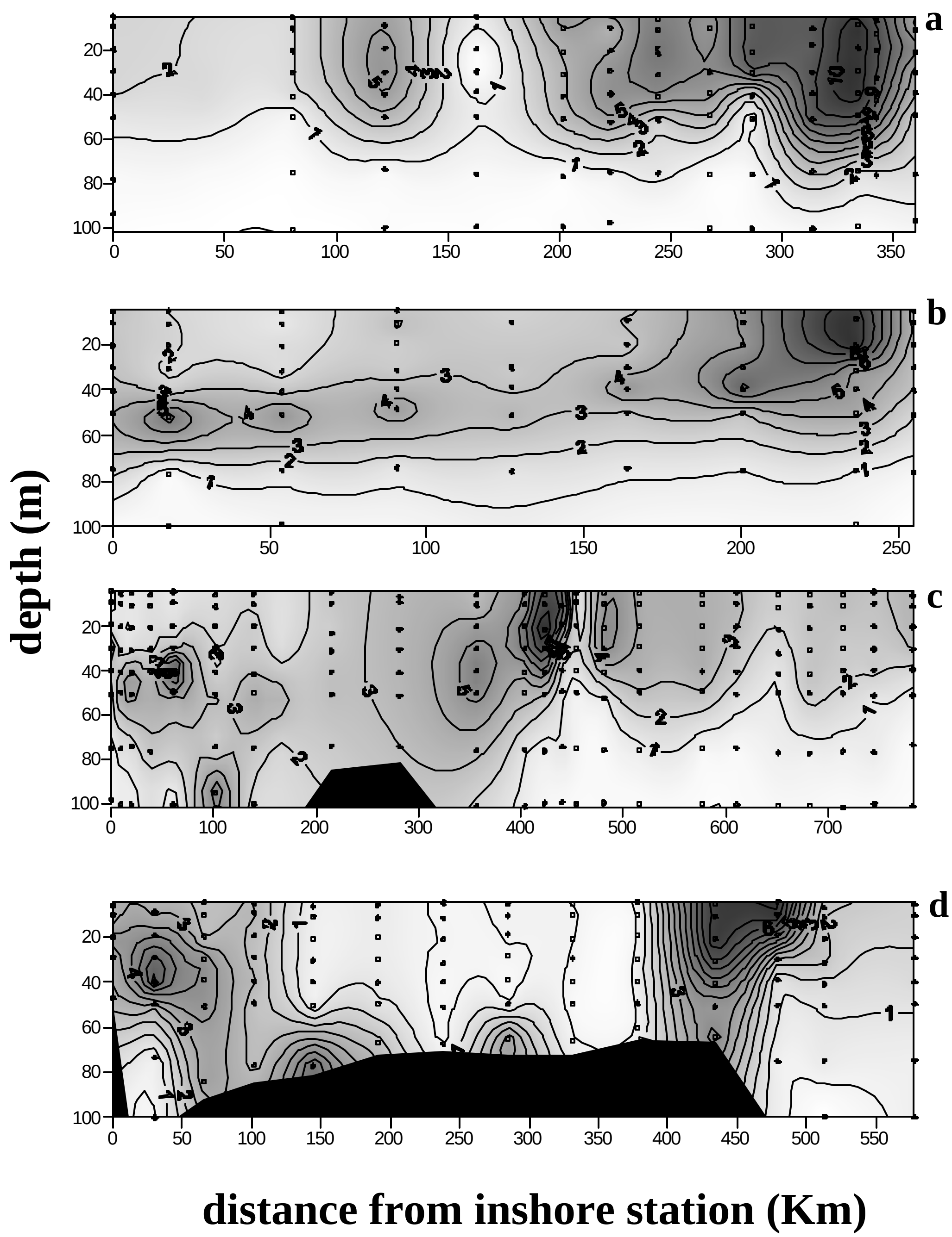

Figure 16. Vertical profiles of chlorophyll a versus distance from the inshore station during Summer 2000 surveys for (a) Beachy Island, (b) Makkovik Bank, (c) Seal Island, (d) White Bay (e) Funk Island, (f) Bonavista Bay, and (g) Flemish Cap transects. Bottom bathymetry shown in solid black. Sample locations on contour plots shown by open circles.

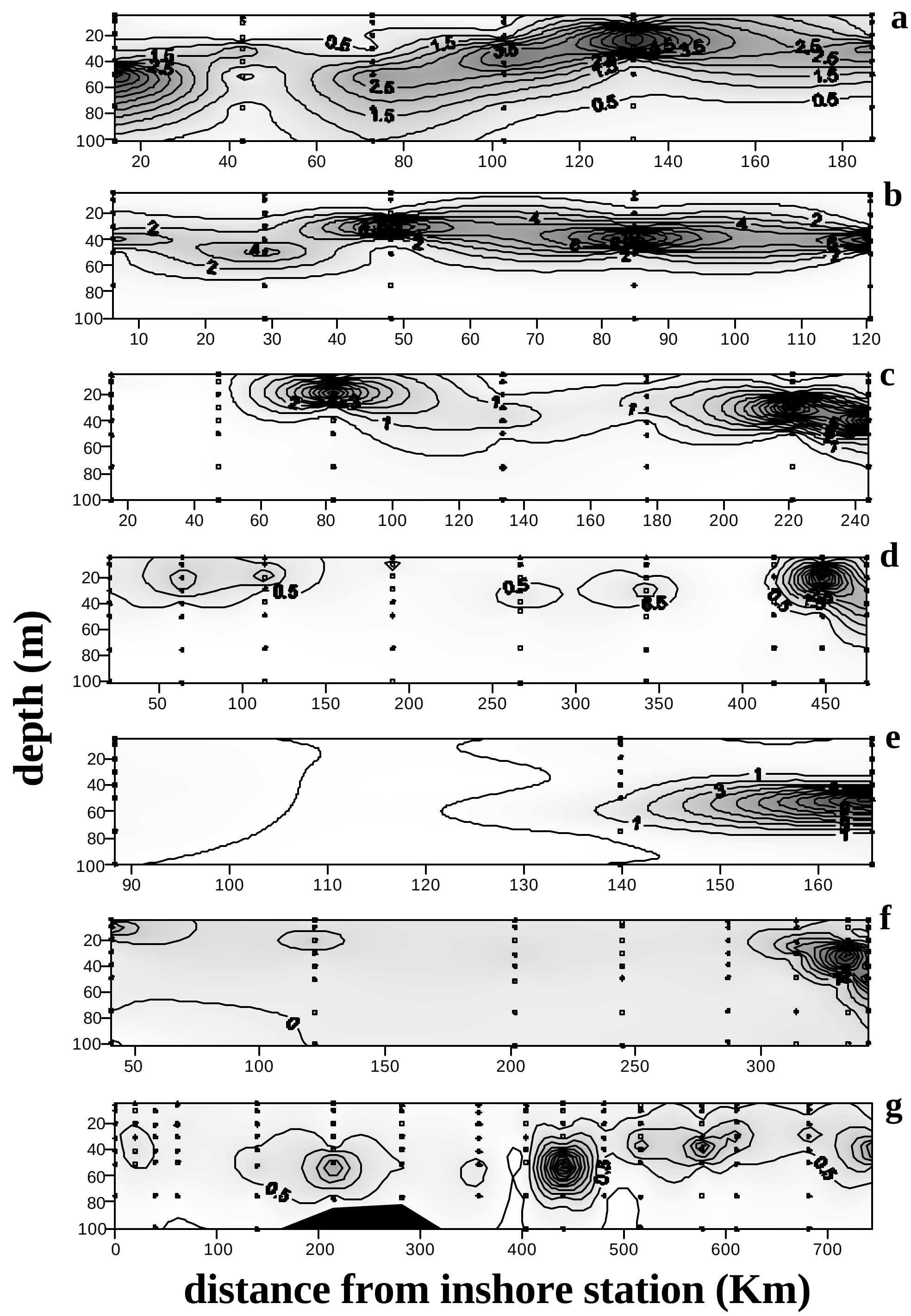

Figure 17. Vertical profiles of chlorophyll a versus distance from the inshore station during Fall 2000 surveys for (a) Bonavista Bay, (b) Station 27 line, (c) Flemish Cap, and (d) southeast Grand Banks transects. Bottom bathymetry shown in solid black. Sample locations on contour plots shown by open circles.

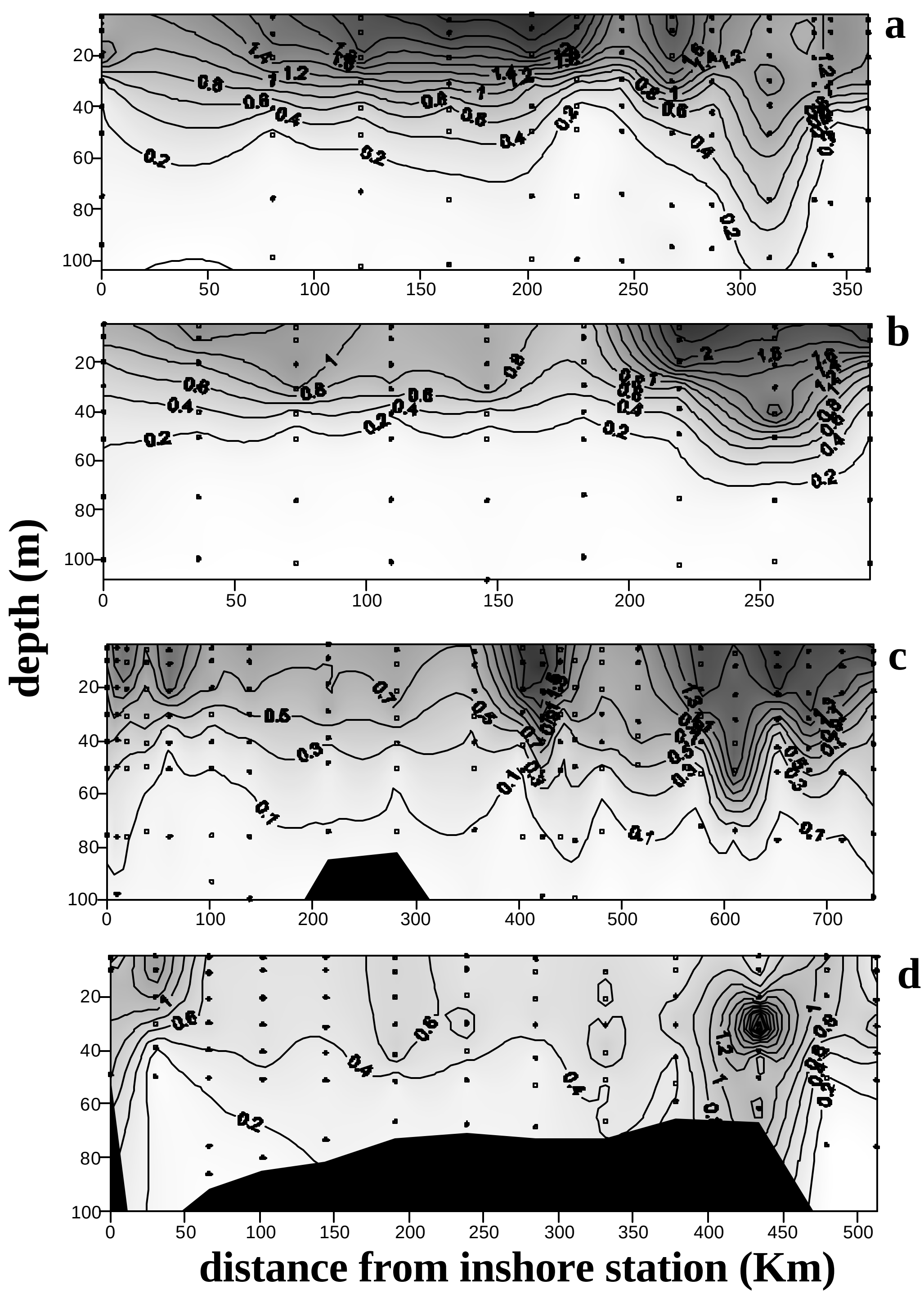

Figure 18. Box whisker plots of cell density (Log_{10} numbers/L) of the three major taxonomic groups of phytoplankton sampled during the spring, summer and fall oceanographic surveys of 1999 and 2000. The number of stations analyzed varied considerably with 12, 28 and 18 samples processed in the spring, summer and fall of 1999, whereas the same 7 stations were used from the three surveys in 2000.

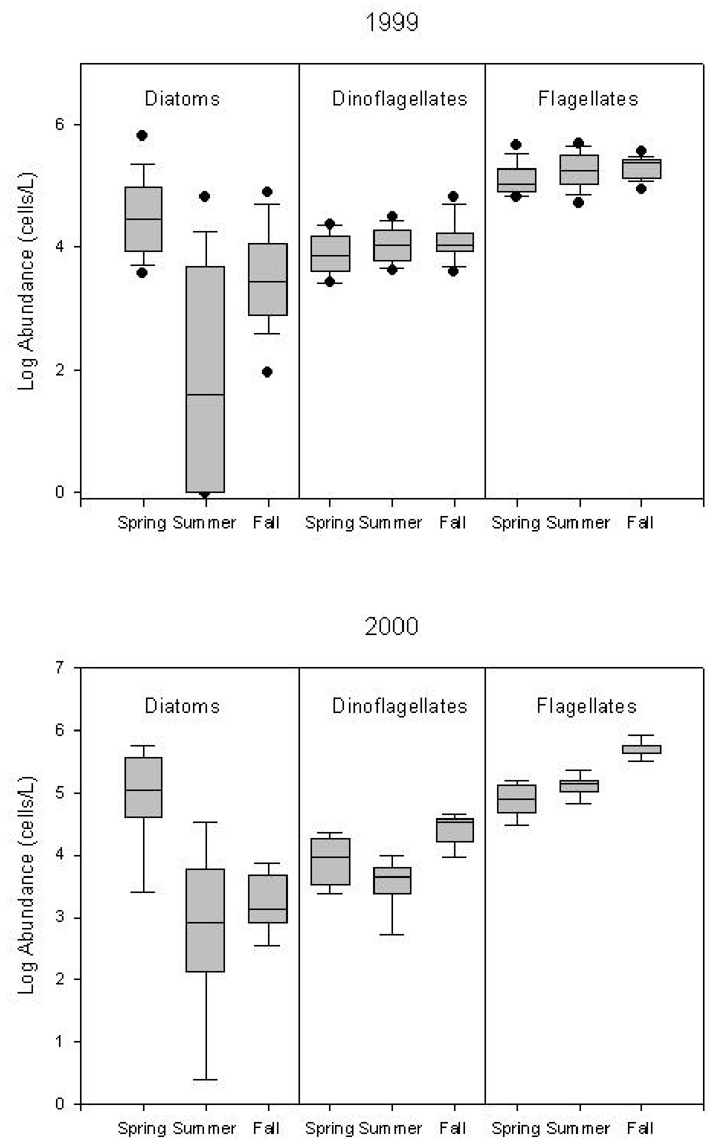

Figure 19. Overall abundance (a), size fractionated dry weight (b), relative species composition during 2000 (c) and average species composition 1996-99 (d) of zooplankton sampled at Station 27 using a 202 μm mesh net.

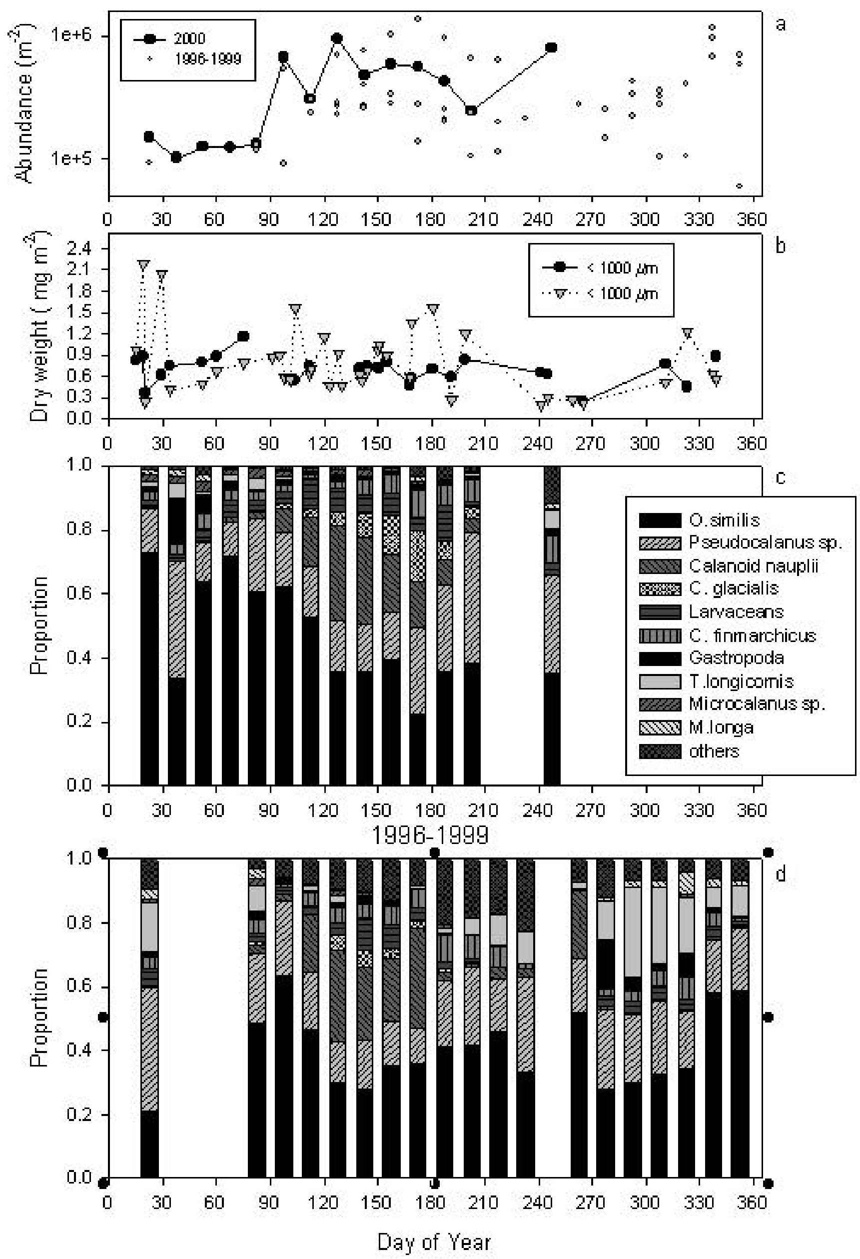

Figure 20. Time series of Shannon's Entropy index (a) and of the ratio of large-to-small copepods (b) from Station 27 during 2000 (closed circles linked by lines). The small grey circles show the distribution of previous observations (1996-1999).

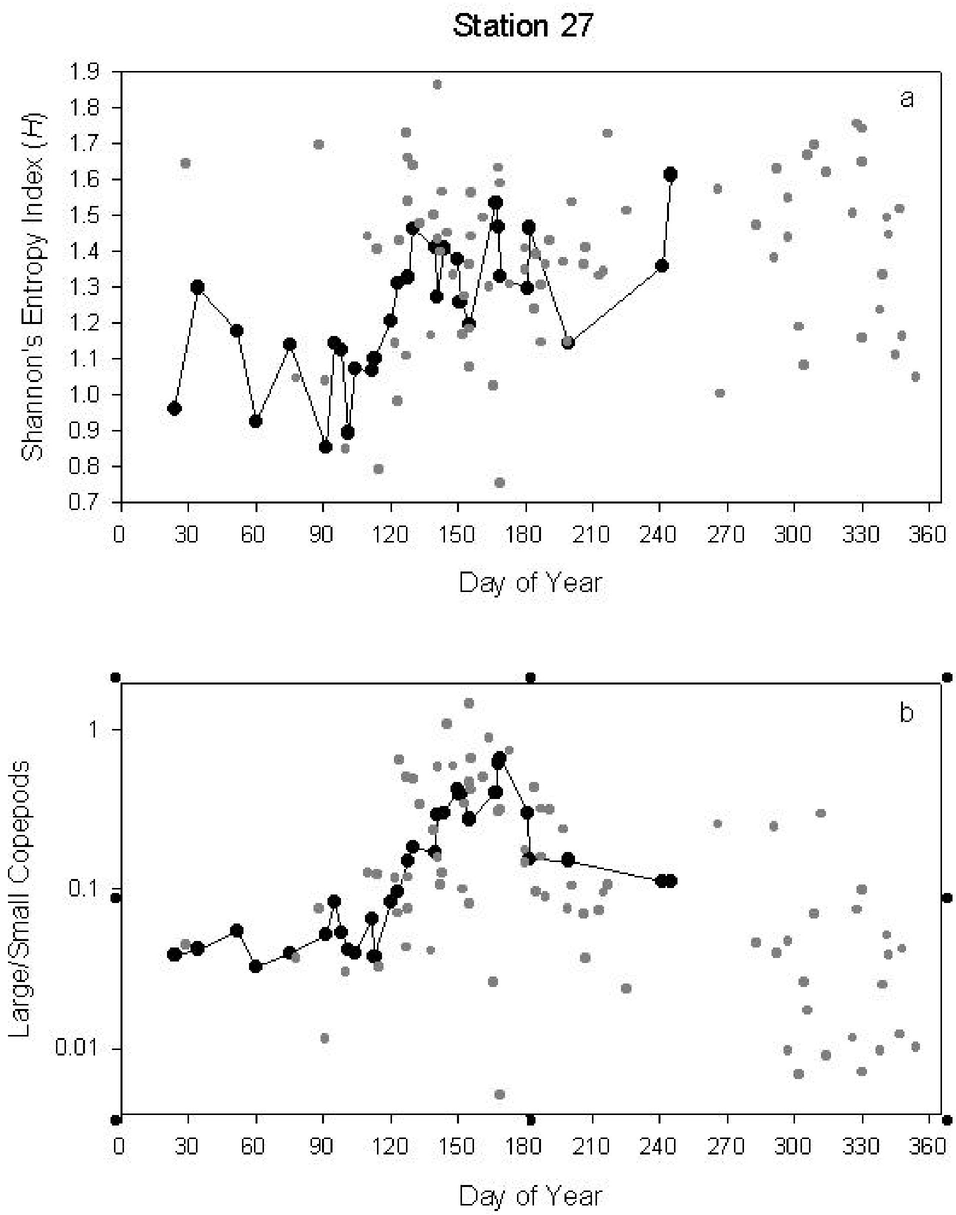

Figure 21. Time series of abundance (m^{-2}) of five dominant taxa sampled at Station 27 during 2000 (black circles linked by lines) and 1999 (grey circles).

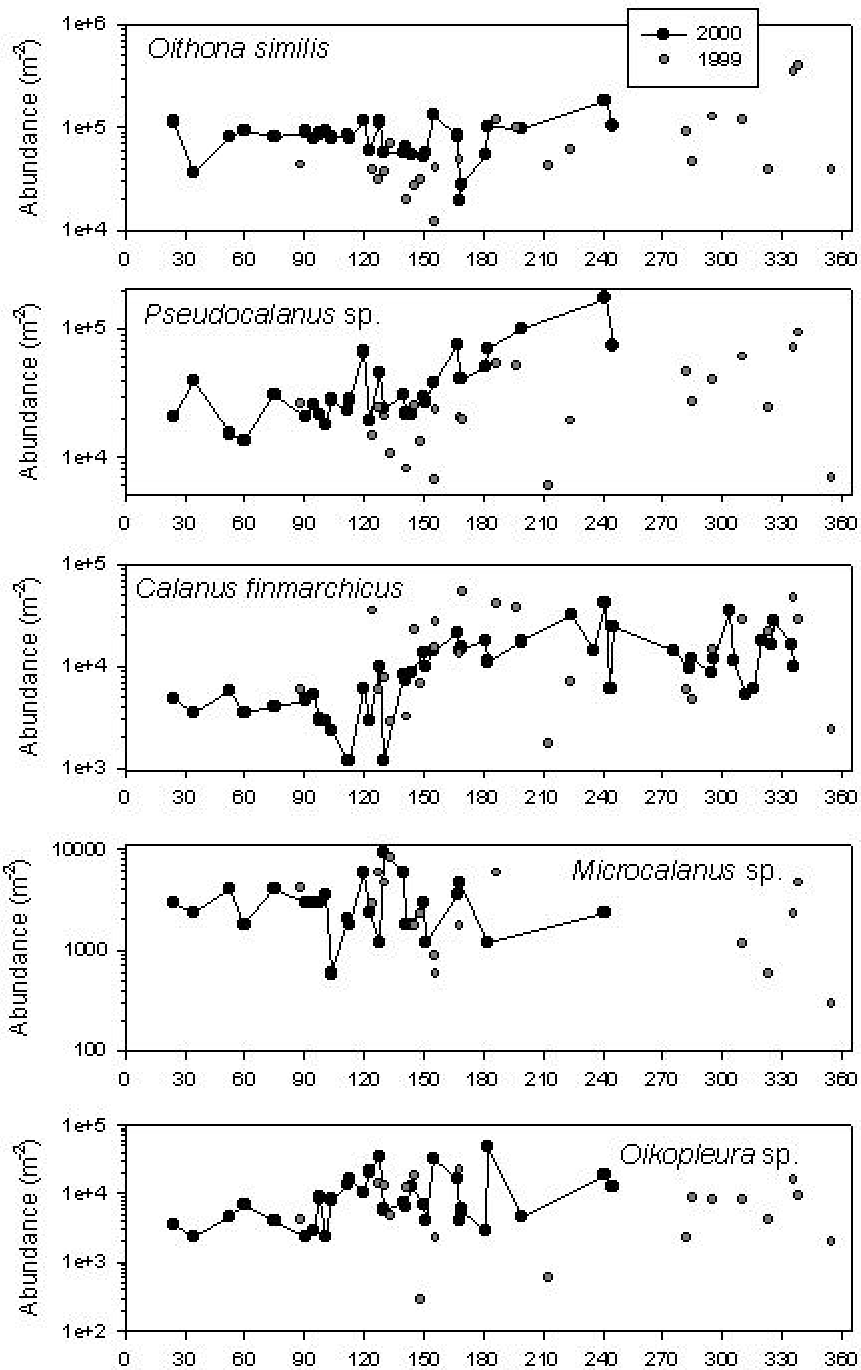

Figure 22. Time series of copepodites of *Calanus finmarchicus* and *C. glacialis* (a), of large calanoid nauplii caught by the 202 µm mesh net (b), and relative abundance of nauplii per adult C VI during 2000 (linked symbols) and from previous observations.

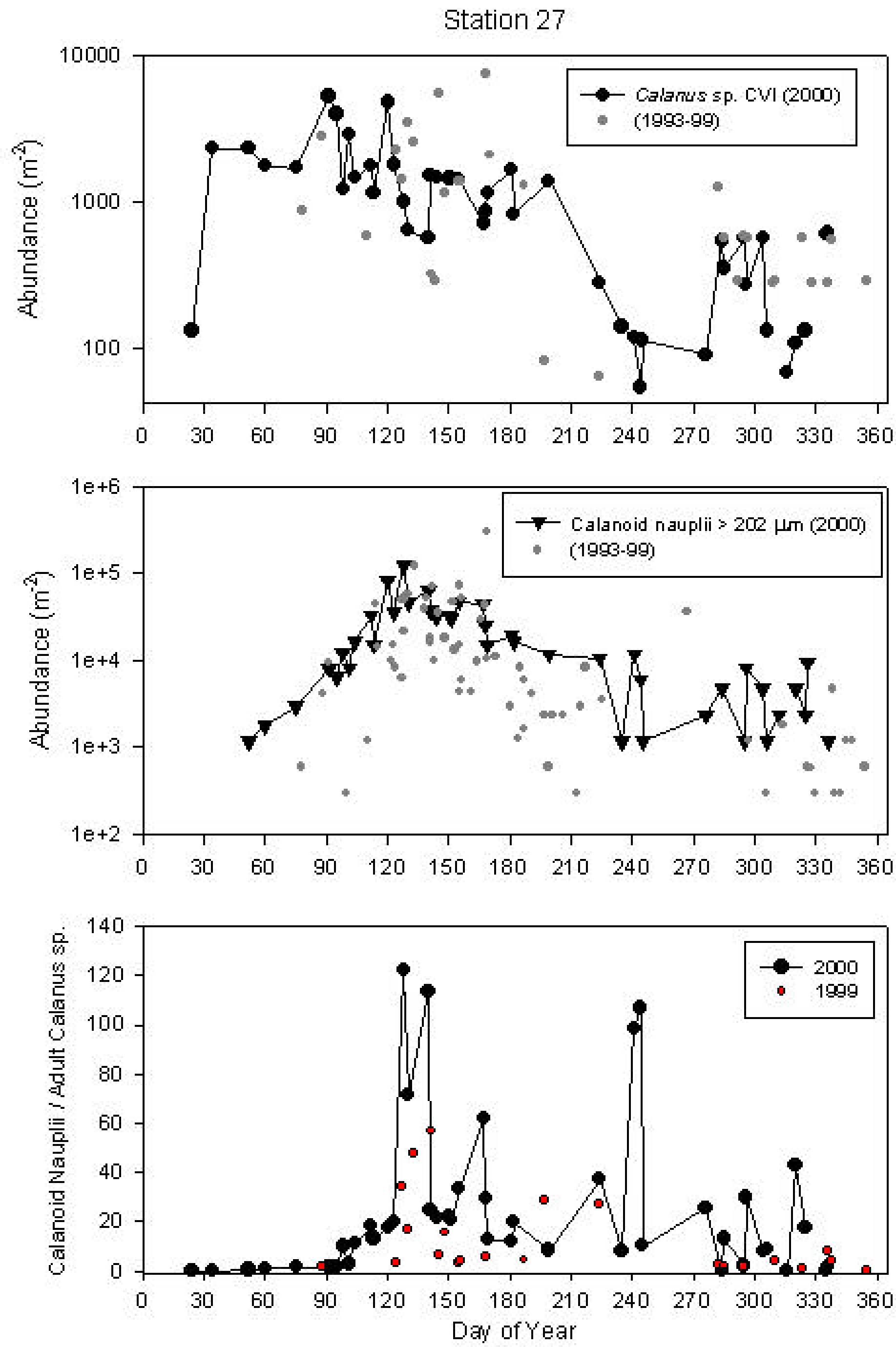

Figure 23. Total abundance of copepod nauplii from vertical plankton samples using 70 µm mesh net.

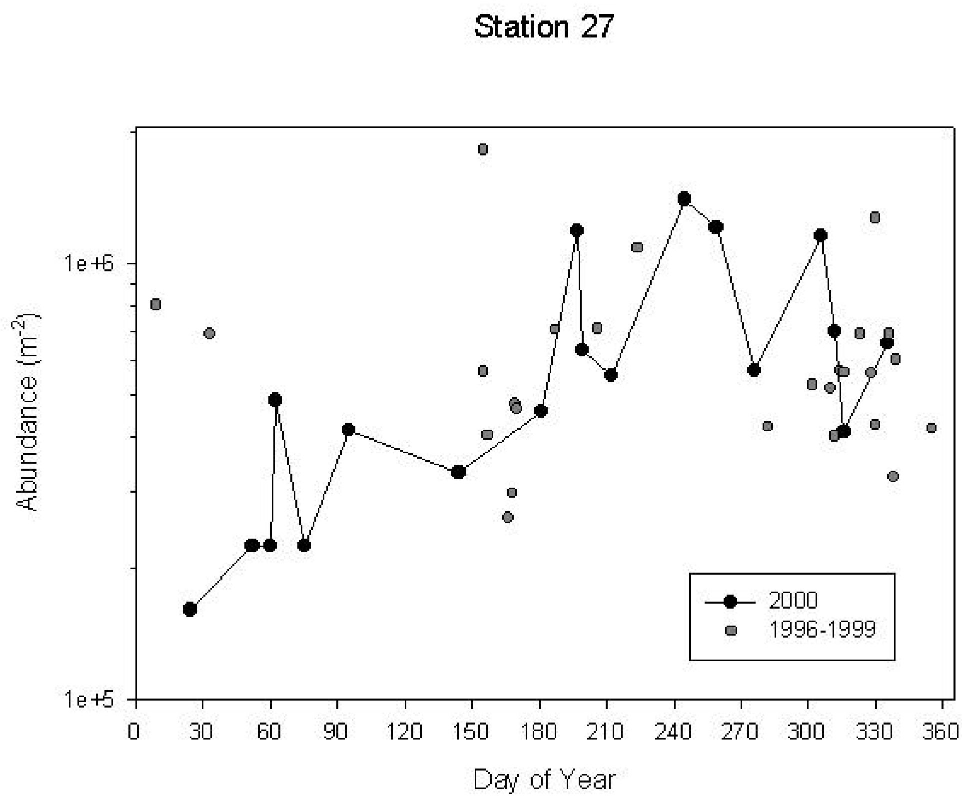

Figure 24. Stage composition of *Calanus finmarchicus* copepodites from Station 27.

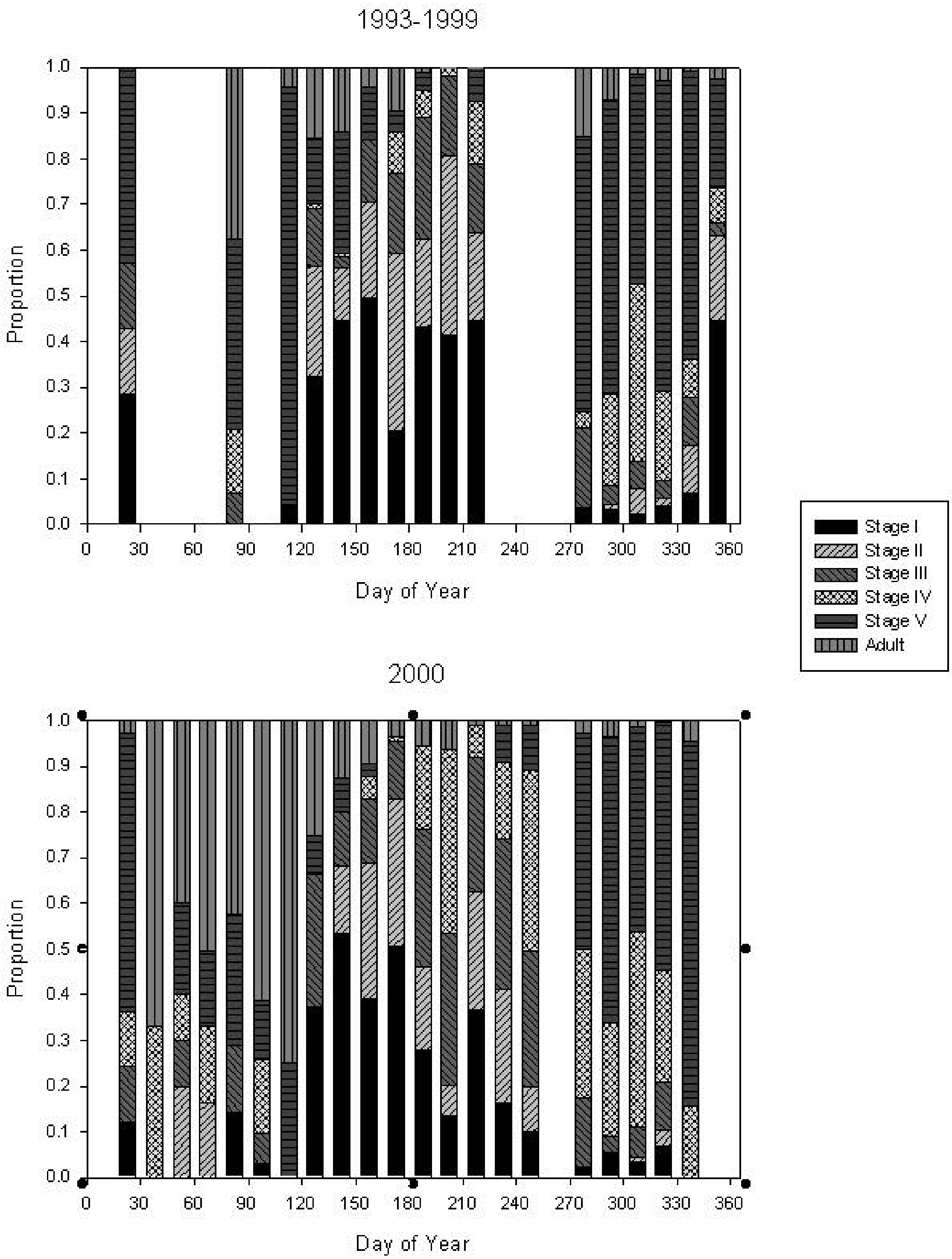

Figure 25. Total zooplankton abundance (m-2) from the 202 µm mesh net during the 1999 (open circles) and 2000 (grey circles) summer oceanographic surveys.

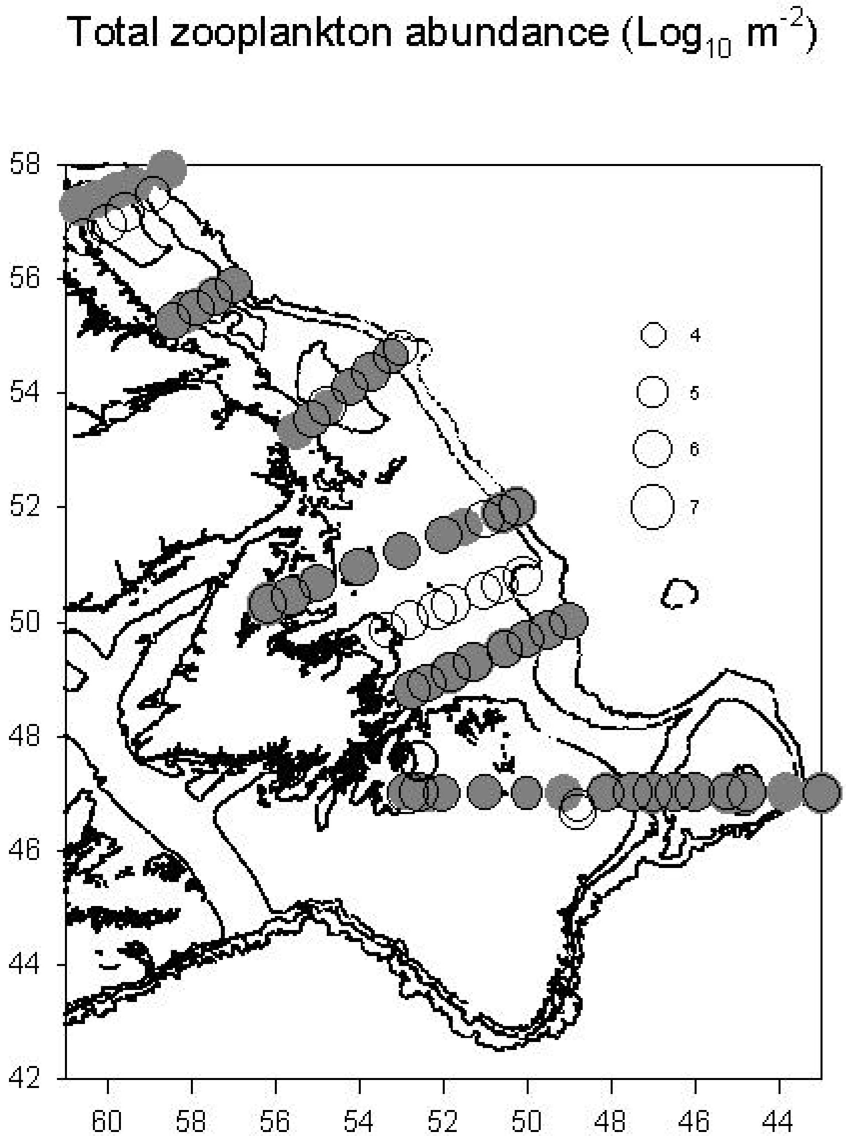

Figure 26. Distribution of *C. finmarchicus* and *Pseudocalanus* sp. (all stages combined) from the (a) summer and fall surveys of 1999 and the (b) spring and summer surveys of 2000.

a

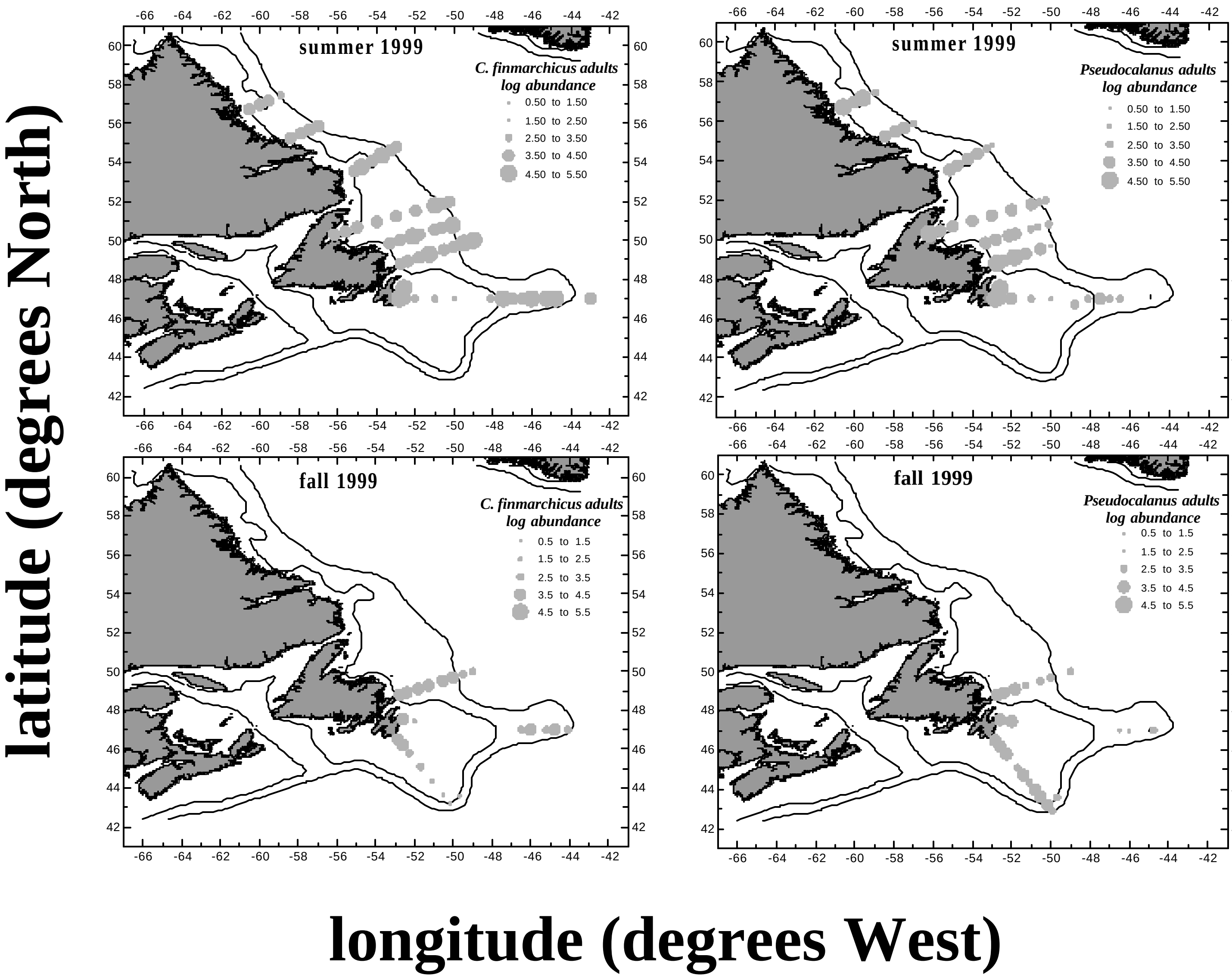

Figure 26. Continued.

b

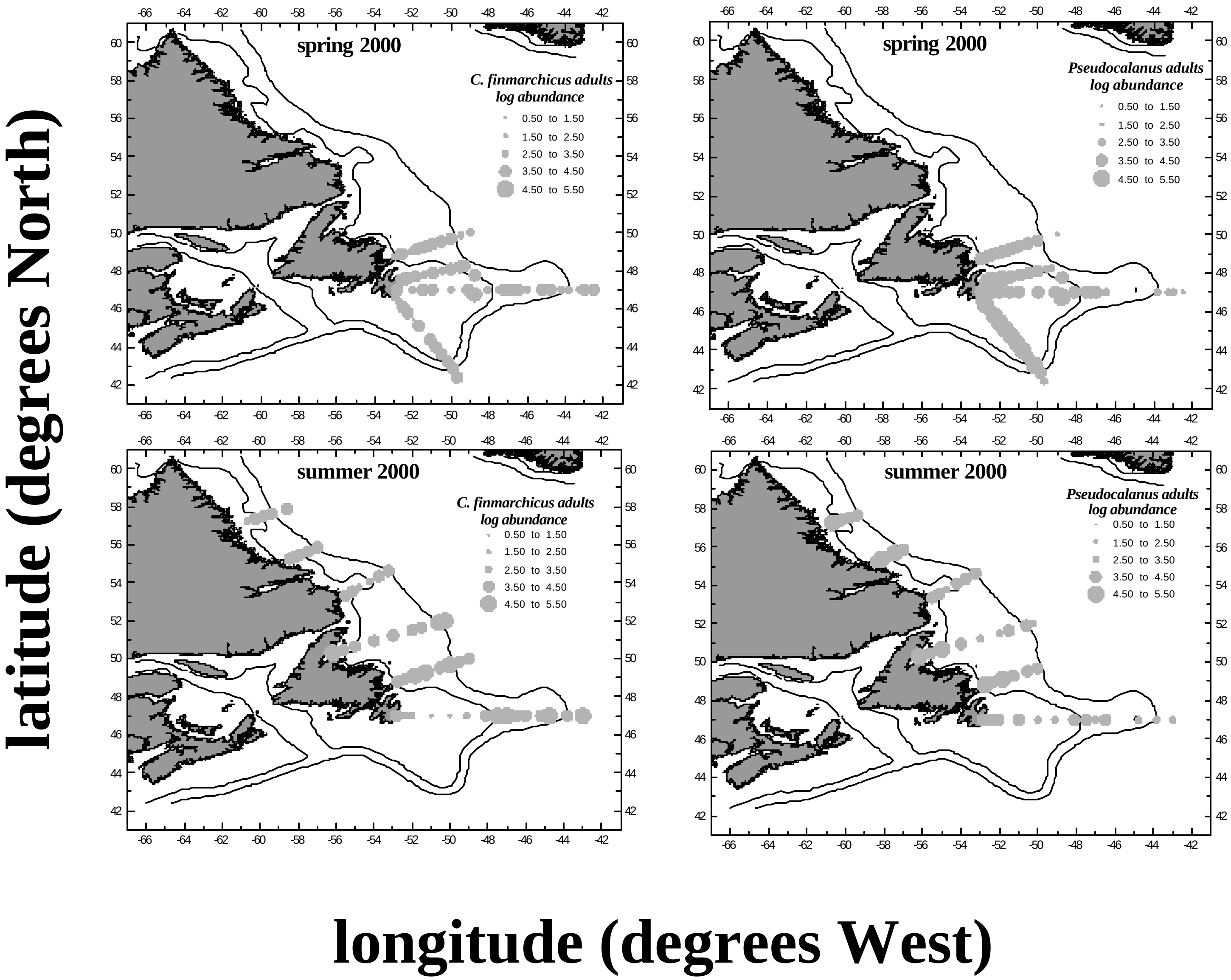

Figure 27. Distribution of zooplankton communities, as determined from discriminant analysis, during the summer oceanographic surveys of 1999 and 2000. The closed circles denotes a community dominated by *Pseudocalanus* sp., the inverted triangles denote the community dominated by *C. finmarchicus*, and the squares denote the community heavily dominated by *O. similis*. All three species are present in most of the samples but their relative proportions vary considerably (Table 2).

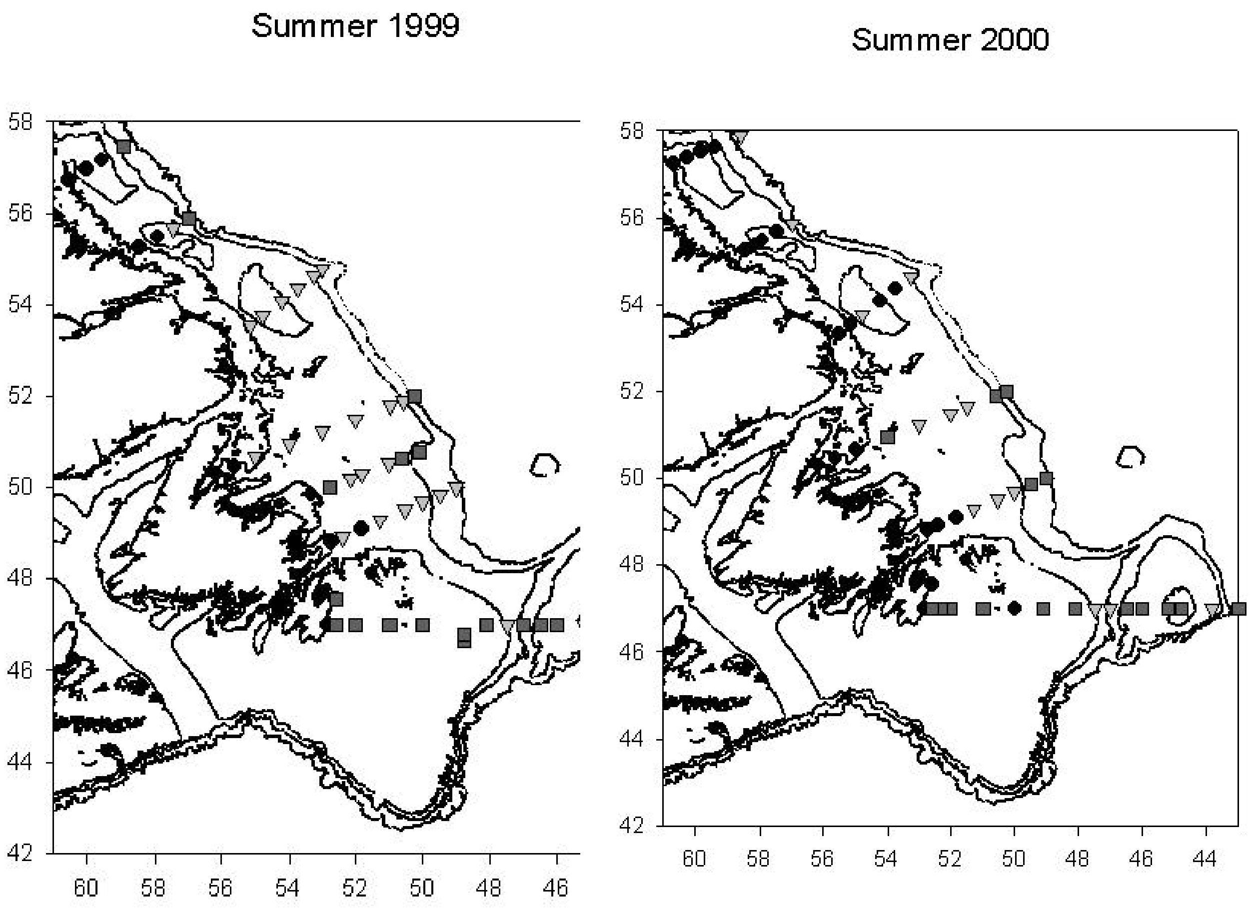

Figure 28. Relative distribution of copepodite stages of *C. finmarchicus* from the transects sampled in the spring, summer and fall surveys. On the left are averages based on data collected during the 1996-99 period, with the time span within the year shown at the top of each panel. On the right are the observations from 2000 for the three cruises listed in Table 1. Transect abbreviations are; SE, Southeast Shoal; FC, Flemish Cap; BB, Bonavista Bay; WB, White Bay; SI, Seal Island; MB, Makkovik Bank; NB, Nain Bank.

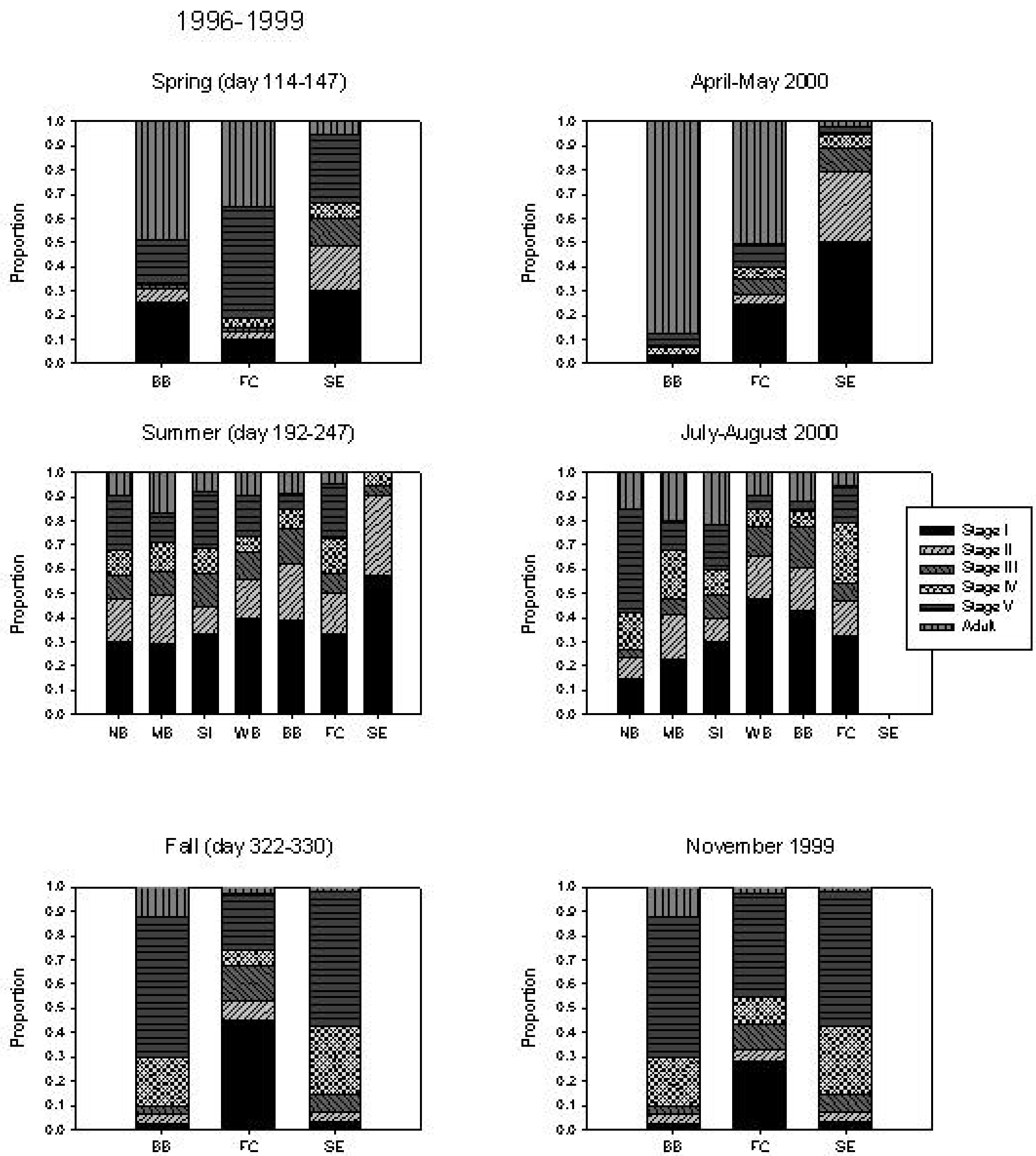

Figure 29. Relative distribution of copepodite stages of *Pseudocalanus* sp. from the transects sampled in the spring, summer and fall surveys. On the left are averages based on data collected during the 1996-99 period, with the time span within the year shown at the top of each panel. On the right are the observations from 2000 for the three cruises listed in Table 1. Transect abbreviations are; SE, Southeast Shoal; FC, Flemish Cap; BB, Bonavista Bay; WB, White Bay; SI, Seal Island; MB, Makkovik Bank; NB, Nain Bank.

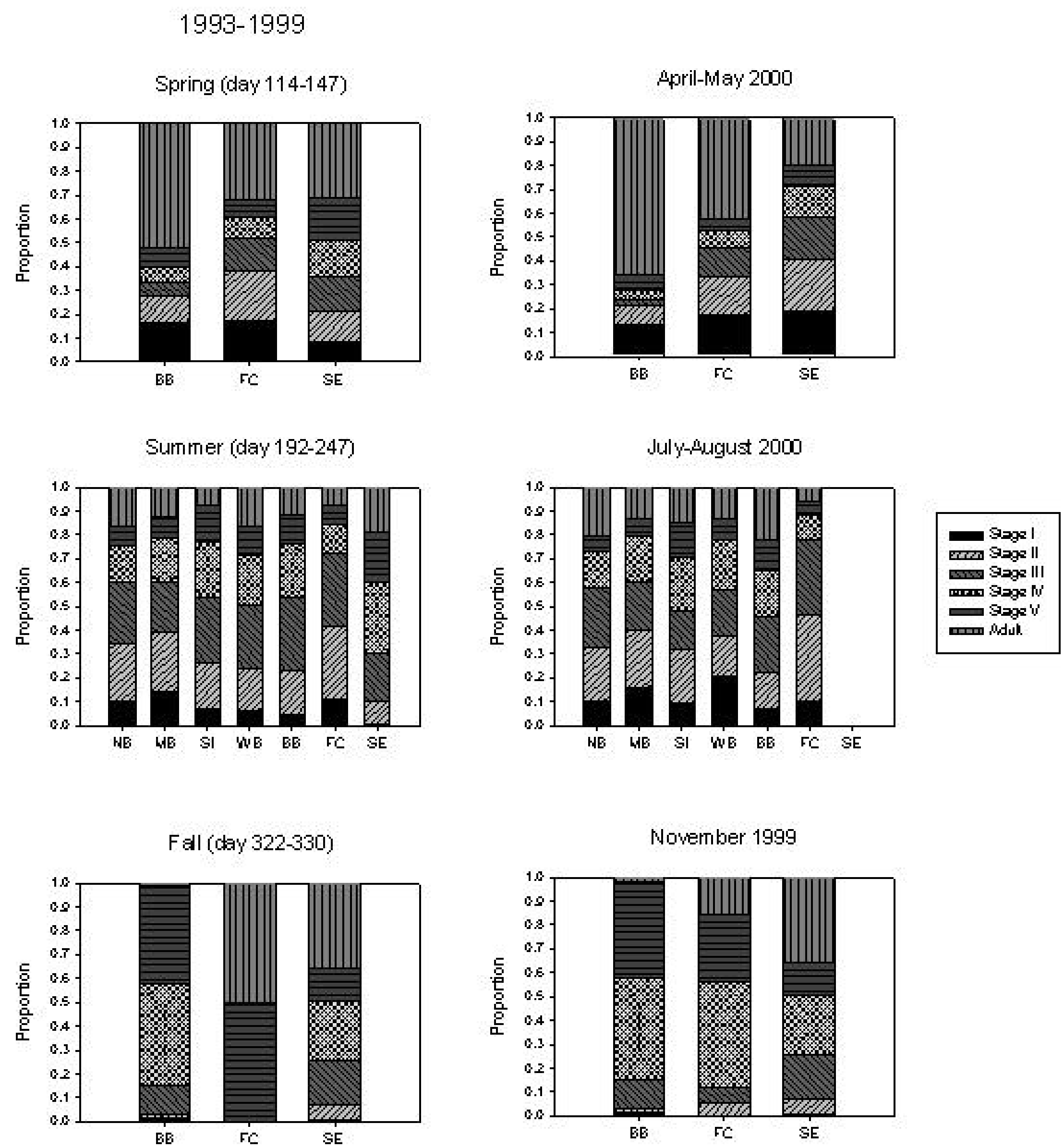

Figure 30. Cumulative frequency distribution of large calanoid nauplii (left) and adult C VI (*C. finmarchicus*, *C. glacialis*) (right) catches from the summer oceanographic surveys from 1999 and 2000.

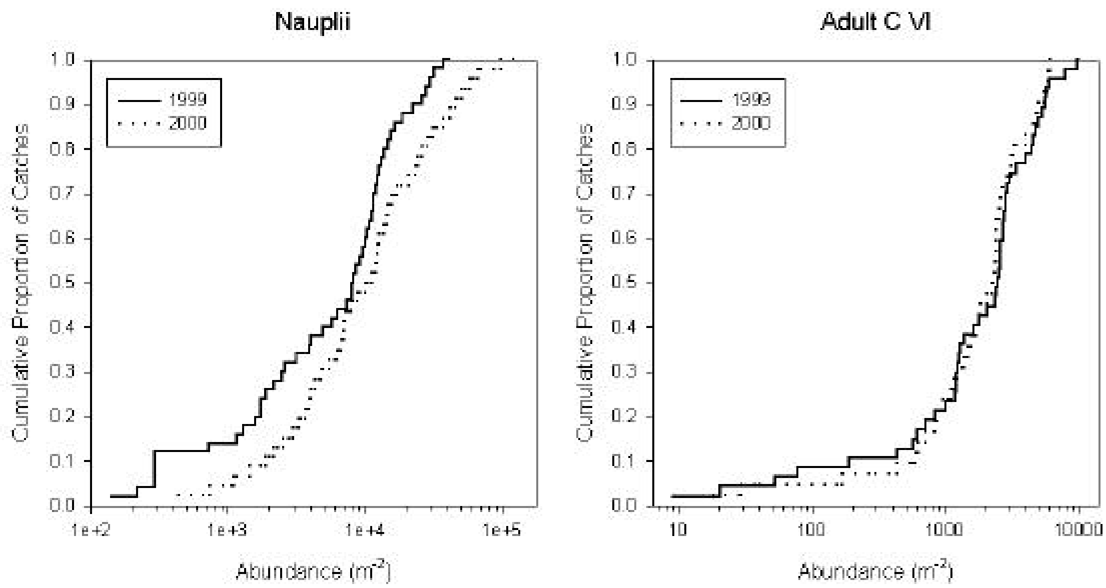

Figure 31. Spatial distribution of large calanoid nauplii (left) and adult C VI (*C. finmarchicus* + *C. glacialis*) copepodites from the 1999 (open circles) and 2000 (grey circles) summer oceanographic surveys. Scale legends are on the right of each plot.