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Biological and Chemical Oceanographic conditions on the Newfoundland Shelf during 2002.

Conditions océanographiques, biologiques et chimiques sur le plateau Terre-Neuvien au cours de l'année 2002.

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ABSTRACT

We review the information concerning the seasonal and interannual variations in the concentrations of chlorophyll *a*, major nutrients, rates of primary production, as well as the abundance of major taxa of phytoplankton and zooplankton measured from Station 27. We focus on temporal and spatial series of the different biological, chemical, optical, and physical measures during 2002 but contrast those observations with previous information from earlier periods when data are available. The vertical attenuation coefficient increased nearly two-fold during the spring bloom in 2002 at the fixed coastal station compared to previous years, confining the penetration of incident solar radiation to shallower depths and the general reduction in the euphotic depth. The trend in optical conditions at Station 27 was not consistent with the general reduction in attenuation across different oceanographic sections and seasons in 2002, leading to deeper euphotic depths. The annual climatology for incident solar radiation suggested that recent solar radiation measurements collected during 2001-02, were among the highest recorded during the available time series for the months of April through to October. Water column stability and heating, inferred from stratification and integrated temperature, showed consistent trends between the seasonal occupations of Station 27 and AZMP sections. In general, stratification and integrated temperature in the upper 50m across the Newfoundland and Labrador Shelf were lower compared to earlier years. Time series of major nutrient inventories at Station 27 showed differences between years. The seasonal inventories of silicate and nitrate in the upper 50m were 2-3-fold higher along most oceanographic sections compared to earlier years (2000-01). Similar positive trends in the deep inventories were apparent for the southern Grand Banks, but smaller differences were observed along the other sections. The magnitude of the spring bloom has increased during the past 3 years peaking in 2002 and coincided with a similar trend in primary productivity at Station 27 during this period. Although the spring inventories of chlorophyll a (proxy of phytoplankton biomass) were higher in 2002 at Station 27 compared to earlier years, the pattern at the fixed station was not reflected in the offshore waters, where a negative trend was observed along the sections. Another prolonged maxima in mixed layer depth was observed at Station 27 during late winter-spring 2002 and may have contributed to the timing and short-duration (54 days) of the bloom. Both 2001 and 2002 had higher wind stress compared to the conditions observed during 2000. In 2001, this prolonged maxima coincided with a delay in the timing of the spring bloom and shortened it's duration by one-half compared to 2000. Major groups of phytoplankton were enumerated seasonally at the fixed station and along selected stations on oceanographic sections. The most notable difference observed between recent years was the increase in Diatom abundance during the spring bloom, and the presence of a fall bloom of coccolithophorids, not previously observed at Station 27.

RÉSUMÉ

Nous passons en revue les données de variations saisonnières et interannuelles des concentrations de chlorophylle *a* et des principaux éléments nutritifs, des taux de production primaire et de l'abondance des principaux taxons de phytoplancton et de zooplancton à la station 27. Nous mettons l'accent sur les séries temporelles et spatiales des diverses mesures biologiques, chimiques, optiques et physiques faites en 2002, mais en les comparant avec les données disponibles pour des années antérieures. Au cours de la prolifération phytoplanctonique printanière de 2002, le coefficient d'atténuation vertical à la station côtière fixe a presque doublé par rapport aux années précédentes. Cela signifie que le rayonnement solaire incident y pénétrait moins profondément et que la zone euphotique était généralement réduite. En 2002, l'évolution des conditions lumineuses à la station 27 ne concordait pas avec la baisse générale de l'atténuation sur les différents transects océanographiques et au cours des différentes saisons, qui correspond à une hausse de la profondeur de la zone euphotique. Selon la climatologie annuelle du rayonnement solaire incident, les mesures de rayonnement effectuées en 2001 et en 2002 comptent parmi les plus élevées des séries temporelles disponibles pour les mois d'avril à octobre. La stabilité et le réchauffement de la colonne d'eau, calculés à partir des données de stratification et de température intégrée, ont montré des tendances semblables à la station 27 et sur les transects du PMZA. En général, la stratification et la température intégrée dans les premiers 50 m de profondeur sur la plate-forme de Terre-Neuve et du Labrador étaient inférieures à celles des années précédentes. Les séries temporelles des concentrations des principaux éléments nutritifs à la station 27 ont varié d'année en année. En 2002, les concentrations saisonnières de silicate et de nitrate dans les premiers 50 m de profondeur étaient de deux à trois fois supérieures sur la majorité des transects océanographiques, par rapport aux années précédentes (2000 et 2001). Nous avons observé des tendances à la hausse semblables pour les concentrations en profondeur dans le secteur sud des Grands Bancs, mais les différences étaient moindres sur les autres transects. L'ampleur de la prolifération phytoplanctonique printanière a augmenté au cours des trois dernières années, atteignant un maximum en 2002, et elle a coïncidé avec une tendance semblable de la productivité primaire à la station 27. Bien que les concentrations printanières de chlorophylle *a* (mesure indirecte de la biomasse du phytoplancton) à la station 27 étaient supérieures en 2002 par rapport aux années précédentes, la situation était différente dans les eaux extracôtières où nous avons observé une tendance à la baisse sur les transects. Nous avons constaté une autre période prolongée de profondeur maximale de la couche mélangée à la station 27 à la fin de l'hiver et au printemps 2002, laquelle peut avoir contribué au commencement et à la courte durée (54 jours) de la prolifération phytoplanctonique. La force d'entraînement du vent était plus élevée en 2001 et en 2002 qu'en 2000. En 2001, la période prolongée de profondeur maximale a coïncidé avec un retard de la prolifération printanière et elle a entraîné une baisse de 50 % de la durée de celle-ci par rapport à 2000. Nous avons dénombré les principaux groupes de phytoplancton présents chaque saison à la station fixe et à

certaines stations sur les transects océanographiques. Les différences les plus remarquables observées au cours des dernières années étaient l'augmentation de l'abondance des diatomées au cours de la prolifération printanière et la prolifération automnale de coccolithophoridés, jamais observée auparavant à la station 27.

Introduction

We review standard optical, chemical, selected physical and meteorological indices, and biological oceanographic conditions on the Newfoundland and Labrador Shelf during 2002. More frequent directed sampling from research vessels and ships-of-opportunity at Station 27 and the completion of three surveys on the Newfoundland Shelf during 2002 provided good spatial and temporal series coverage of standard variables which provides a good foundation for comparison with previous years. Collections and standard AZMP variables are based on sampling protocols outlined by the Steering Committee of the Atlantic Zonal Monitoring Program (AZMP). A number of non-standard AZMP variables are also presented for additional information. Protocols for additional measures are described in Pepin and Maillet (2001). Observations presented in this document are based on surveys listed in Table 1 and Figure 1.

Fixed Station – Seasonal and interannual variability in water column optics and solar radiation

The availability of light for photosynthesis in an aquatic ecosystem is determined by the penetration of the light field (Kirk 1994) and regulated by the vertical attenuation coefficient (K_d), which is related to dissolved and colored substances and particulate matter in seawater. Time series of K_d at Station 27 showed similar trends during 2000-02 (Figure 2). The vertical attenuation coefficient (K_d) was estimated by:

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

where B(z) is the concentration of chlorophyll *a* (mg m^{-3}) at depth (z) in meters. The additional coefficients in the above equation are related to the components of pure seawater (0.027 m^{-1}) and dissolved substances (0.015 m^{-1}). The average value of K_d was calculated for the 5-50m depth. Values of attenuation estimated from *in-situ* downward photosynthetic active radiation (PAR) (data not shown) in the upper 50m compared well with vertical attenuation coefficient estimated from the Platt *et al.* 1988 model shown in Figure 2. Attenuation increased rapidly in response to the onset of the spring bloom from initial background levels of ca. 0.1 m^{-1}. The trend in the series shows an increasing K_d during the production cycle related principally to the observed increase in chlorophyll *a* concentration. The trend in the vertical attenuation coefficient indicated higher extinction of light (by factor of 2) in the water column in 2002 in comparison to earlier years. Periodically, small changes in K_d were observed during summer and early fall throughout the time series. Measures of K_d provide estimates of euphotic depth (depth of the 1 % light level) based on:

Euphotic depth (m) = $4.6 / K_d\_PAR$

The euphotic depth defines the boundary to which significant photosynthesis can occur, and is often used to constrain primary production estimates. Time series of euphotic depth varied seasonally at Station 27 with shallow depths of ca. 20m during the spring bloom while deeper values of ca. 50-80m observed thereafter (Figure 2). The range in euphotic depth was greatest during 2002 with the observed spring bloom values of < 20m and post-bloom values of > 80m for several weeks in duration compared to the earlier series.

Knowledge of the flux of radiant energy is essential to interpret variability in the water column and primary productivity. Time series of incident downward PAR irradiance collected at a ground station in St. John's, Newfoundland (47.52 N, 52.78 W) provide near-continuous measures to supplement limited *in-situ* PAR observations collected during sample occupations at Station 27 (Figure 2). Measurements were initiated in July 2001 with the use of a Li-Cor datalogger (LI-1400) and quantum PAR irradiance sensor (LI-190SA) attached to the roof at the Northwest Atlantic Fisheries Centre in St. John's, NL. Total daily incident PAR shows a strong seasonal component and high variability throughout the annual cycle. The average of daily incident PAR and standard deviation, total PAR and total daily insolation for each month of the year during 2002 showed that December had the lowest average total daily PAR at 5.95 moles m^{-2} and highest in July at 40.23 mol m^{-2} (Table 2). Monthly time series of global sky radiation obtained from Environment Canada and converted to PAR (Ting and Giacomelli 1987) from 1964-1998 showed a maximum annual variability of ca. 25 % (Figure 3). The annual climatology for solar radiation suggested that recent PAR measurements collected at NWAFC station during 2001-02, were among the highest recorded during the available time series for the months of April through October (Figure 3).

Variability of optical measures in the vertical attenuation coefficient and euphotic depth during 2002 indicated that spring (Mar-May) shows the largest change compared to other seasonal time periods (Figure 4). The mean percent seasonal change in 2002 showed an increase of 60 % in the vertical attenuation coefficient and 35 % reduction in euphotic depth during spring compared to earlier years (Figure 5). Smaller differences were observed in optical measures during the other seasonal periods in 2002 in relation to earlier years.

Fixed Station – Seasonal and interannual variability in meteorology and water column structure

Daily time series of atmospheric pressure and wind stress (0.02 * wind speed^2) were estimated from hourly values obtained from the Meterological Canadian Service, Environment Canada[1] during 2000-02. Time series of physical measures including stratification index (Craig *et al*. 2001), mixed layer depth, and integrated temperature (upper 50m) were estimated at Station 27 during the same time

[1] http://www.meds-sdmm.dfo-mpo.gc.ca/zmp/sl_stations_e.html

period (Figure 6). The passage of low pressure systems coupled with higher wind stress during the late fall and winter was apparent during 2001-02. Conditions during the winter of 2000 were calmer with reduced frequency of low pressure systems and lower wind stress in comparison to 2001-02. The magnitude, timing, and duration of stratification showed similar trends during the 2000-02 time series. The stratification index reached maxima in late August-early September and minima in December through March. Although the magnitude of stratification was slightly greater in 2002, the duration and onset of stratification was shorter and delayed compared to earlier years (Figure 6).

The mixed layer depth (MLD) series, taken as the depth centre of the pyncocline, revealed apparent maxima in January-April, followed by an abrupt shoaling in late spring (May-June) and then gradually increasing during the fall. Larger, prolonged maxima in MLD were observed in 2001-02 compared to 2000. Deepening and prolonged deep MLD is likely related to reduced water column stability due to increased wind stress observed during the winters of 2001-02 and may have contributed to observed variation in the timing and magnitude of phytoplankton blooms.

The upper 50m integrated temperature series displayed a strong seasonal cycle with maxima reached in September-October and minima in March-April. The integrated temperature series displayed small interannual variation in the timing and magnitude at the fixed station. On average, thermal conditions in the upper 50m were cooler in 2002 compared to earlier years at Station 27.

Seasonal variations in the stratification index and integrated temperature were apparent during 2002 at Station 27 (Figure 7). Average levels of the stratification index were low during winter-spring (< 0.006) and increased near an order of magnitude during summer, and then followed by a 2-fold reduction during the fall. A similar pattern of change was observed for integrated temperature with low values (<50 ^{o}Cm) during winter-spring, and consecutive increasing levels during the summer and fall (Figure 7). The percent change in the stratification index in 2002 varied seasonally with positive trends during winter and summer and negative trends during spring and fall when compared to earlier years (Figure 8). The percent change in integrated temperature revealed a strong negative change (> 300%) in 2002 during winter compared to earlier years, but this difference gradually declined during the intervening seasons although remained negative throughout the year (Figure 8).

Fixed Station - Seasonal Variability in Nutrients

We examined the 2002 time series of major nutrients including nitrate (combined nitrate and nitrite, henceforth referred to as nitrate), and silicate and contrasted with data obtained in earlier years at Station 27 (Figure 9). Concentrations of silicate and nitrate were typically > 2 mmol m^{-3} throughout the water column and approached maxima of 16 mmol m^{-3} near the bottom prior to the spring bloom. Concentrations of both major nutrients were depleted rapidly to values < 0.5 mmol m^{-3} within the upper 50m during the bloom and remained very low throughout the latter part of the year until fall when there was a gradual increase in the concentration of both nutrients. The nutricline shoaled periodically during the summer and fall. Evidence in upwelling of these major nutrients from the deep pools was also evident during the latter part of the year, particularly during 2001-02, with concentrations of silicate and nitrate approaching 10 mmol m^{-3} at the base of the euphotic zone. Difference in vertical concentration profiles of both major nutrients were apparent between years. Overall, silicate and nitrate prior to the spring bloom tended to be reduced by 2-3 mmol m^{-3} during 2001 in contrast to 2000 and 2002. Evidence of upwelling in both nutrients was apparent during summer-fall in 2001-02, when concentrations were enhanced at intermediate depths.

Time series of nutrient inventories at Station 27 showed differences between years (Figure 10). Silicate and nitrate inventories in the upper mixed layer (< 50m) showed expected seasonal trends with winter and fall maxima, rapid depletion during the spring bloom, and occasional periodic intrusions during the summer. Sources of these periodic nutrient intrusions may be related to shoaling of deep pools below the mixed layer, wind-induced mixing from passage of storms, and advective transport from the inshore branch of the Labrador current. Both nutrient inventories showed coherence throughout much of the time series. Depletion of upper inventories of nitrate and silicate were more prominent in 2000 during the spring and summer compared to the 2001-02 period. Deep inventories for both nutrients also displayed a substantial (near 2-fold) reduction in 2001-02 compared to the 2000 time series.

Seasonally averaged changes in the upper 50 m silicate and nitrate inventories during 2002 showed winter values in excess of 150 mmol m^{-2}, followed by a rapid reduction to levels < 50 mmol m^{-2} during spring and summer, and increased levels for silicate during fall while nitrate remained depleted (Figure 11). In contrast, the deeper (50-150m) inventories remained in excess of 500 mmol m^{-2} throughout the year across all seasons (Figure 11). As well, the shallow and deep inventories of silicate were larger compared to nitrate across all seasons during 2002. Trends in the upper 50 m silicate and nitrate inventories were negative in 2002 during winter-spring (5-60 %), reversed during the summer with a positive trend (30-60 %), and increased for silicate but, decreased for nitrate during the fall compared to earlier years (Figure 12). The pattern for the silicate deep inventory was negative in 2002 during the fall-winter and positive during spring-summer, while the deep nitrate inventory showed a consistent negative trend across all seasons compared to earlier years (Figure 12).

Nutrient Depletion - Station 27 and Oceanographic Sections

The relative importance in uptake of silicate and nitrate was investigated seasonally at Station 27 and along the oceanographic sections in 2002 (Figure 13). The concentration of silicate versus nitrate at Station 27 in 2002 indicated the uptake of both silicate and nitrate (i.e., intercepts near zero) may be limiting to phytoplankton growth prior to the spring bloom and early post-bloom, while nitrate is more limiting relative to silicate in the fall (i.e., large negative intercept compared to earlier periods). Phytoplankton growth along oceanographic sections was limited by nitrate slightly more than silicate, given the intercept values were negative for the spring and fall Survey's, but clearly indicate the relative importance of both major nutrients given the intercepts were near-zero in all cases. Rates of utilization of major nutrients were similar between Station 27 and oceanographic sections, consistent with earlier observations. The general relationship between silicate and nitrate differed between 2002 and earlier years (Figure 13). All the relationships in 2002 tended to display non-linear patterns compared to earlier years which showed more linear behavior although the scatter in the data was large (Pepin and Maillet 2002).

Fixed Station - Phytoplankton Abundance and Biomass

Vertical profiles of chlorophyll *a* at Station 27 continue to vary in terms of the timing and magnitude of the spring bloom (Figure 14). The initiation of the bloom in 2002 began with subsurface chlorophyll *a* concentrations in the upper photic zone increasing to > 3.0 mg m^{-3} from background concentrations of < 1.0 mg m^{-3} in late March-early April. We use the criteria of integrated chlorophyll *a* levels $\geq$ 100 mg m^{-2} in upper 100m to define start and end times of phytoplankton bloom. The main bloom was detected near mid to late April with integrated chlorophyll *a* concentrations in excess of 1000 mg m^{-2} and extended until the end of May for a duration of 54 days based on discrete chlorophyll *a* concentrations and *in-situ* chlorophyll *a* fluorescence observations. The bloom duration was identical in 2001, but differed substantially in 2000 with the initiation in late February and persisted until the end of May for a duration of ca. 92 days (Pepin and Maillet 2002). Surface chlorophyll *a* distributions across the NW Atlantic detected from SeaWiFS remote sensing data confirmed the approximate timing and duration of the spring bloom in the Avalon Channel region[2]. The depth of the bloom extended slightly deeper in 2002 compared to earlier years (Figure 14). There is no evidence of extensive summer or fall blooms from our discrete measurements during 2000-02, with the exception of a sub-surface deep chlorophyll *a* maximum layer detected at 75m in late July-early August in 2002.

Time series measures of integrated chlorophyll *a* during 2000-02 re-iterated the importance of spring bloom periods in the seasonal dynamics of phytoplankton

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[2] http://www.mar.dfo-mpo.gc.ca/science/ocean/ias/seawifs/seawifs_3.html

abundance at Station 27 (Figure 15). Integration of chlorophyll *a* at the shallow depth strata (0-50m) captured the main trends, but revealed significant amounts of phytoplankton biomass that occur in deeper strata (> 50m), particularly during the spring blooms. The magnitude of phytoplankton production increased during the 3-year series peaking in 2002. The time series of integrated (calibrated) fluorescence revealed nearly identical trends to extracted chlorophyll *a* fluorescence measures during 2000-02, except for peak levels > 1000 mg m^{-2} in early to mid April 2002, when only *in-situ* chlorophyll *a* fluorescence data were available (Figure 15).

To summarize the chlorophyll *a* profiles collected at Station 27 during 2000-02, the vertical structure of phytoplankton biomass 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 of chlorophyll *a* biomass (m), and z_m is the depth of the chlorophyll maximum. The model was fit to chlorophyll *a* extracted from discrete water samples collected at standard depths at Station 27 (Figure 15). The time series of B_o typically varied from 0-1 mg m^{-3} with higher values observed during the spring bloom. Variability in the biomass (h parameter) time series resembled the expected trends in integrated chlorophyll *a* concentration with peak values observed during the spring bloom and the observed increase during the 3-year series. Thickness or spread of the chlorophyll *a* maximum, given by the σ parameter, typically was maximal during the winter and fall and minimal during spring and increased gradually during summer. The depth of the chlorophyll *a* maximum varied seasonally with the tendency for deep maxima to be formed and persist after post-bloom periods, with a gradual shoaling during the fall and sometimes followed by rapid deepening during winter (Figure 15).

The seasonally averaged chlorophyll *a* inventories at Station 27 in 2002 were maximal during spring reaching concentrations of 300 mg m^{-2} and ca. 50 mg m^{-2} during the intervening periods (Figure 16). The seasonal differences in chlorophyll *a* inventories showed lower fall-winter values (40 % less), and higher (10-30 %) spring-summer concentrations in 2002 compared to earlier years (Figure 17).

The cell densities of major taxanomic groups consisting of Diatoms, Dinoflagellates and Flagellates were investigated at near monthly intervals at Station 27 during 2000-02 (Figure 18). Diatoms reached cell densities in excess of $6x10^5$ cells L^{-1} during the spring bloom in 2002, contributing ca. 80 % of the total phytoplankton, but remain at low densities during the other periods. Densities in 2002 were substantially greater compared to earlier years ($1.3\text{-}2.5x10^5$ cells L^{-1} in 2000-01). The concentration of Dinoflagellates were typically lower by an order of magnitude compared to Diatoms, but persisted throughout the time series. Normally

Dinoflagellates represent < 5 % of the total phytoplankton, except during the summer of 2001 when this taxa briefly accounted for > 40 % of the total phytoplankton community due to an unexpected rapid reduction in the concentration of Flagellate cells observed during this time. The Flagellates were the dominant group by numbers reaching concentrations near $5x10^5$ cells L^{-1} but their abundance is more highly variable compared to Diatoms and Dinoflagellates. The high concentrations of Flagellates observed throughout the year in 2000 have not occurred in the latter part of the time series. With the exception of the spring bloom periods, Flagellates made up typically > 80 % of the total phytoplankton community. Although Flagellates dominated the phytoplankton community by numbers, their typical small size (6-8 μm) suggests their contribution to the overall biomass of phytoplankton is limitedthroughout most of the year (C.H. McKenzie pers comm.).

Phytoplankton population composition at Station 27 is dominated seasonally by several key Genera (Pepin and Maillet 2002). Phytoplankton genera present in 2002 not observed in previous years at Station 27 included; Corethron and Dactyliosolen (centric Diatoms); Gonyaulax, Gyrodinium and Oxytoxum (Dinoflagellates); and Phaeocystis, Parvicorbicula, and Emiliania (Flagellates). Extensive blooms of Emiliania huxleyi (coccolithophorids) were observed along the south coast of Newfoundland during summer 2002 and may have contributed to the unusual appearance of coccolithophorids within the Avalon Channel later in the fall where they made up a significant percent (ca. 20 %) of the total Flagellate population.

We measured daily primary production rates at Station 27 from ^{14}C photosynthesis – irradiance (P-E) experiments conducted in the laboratory using seawater collected at 10m depth (see Pepin and Maillet 2001 for a complete description of methods). A total of 39 P-E experiments were conducted throughout different months during 2000-02 (Figure 19). Rates of daily primary production showed elevated values from spring through the fall period, but tended to remain low during late fall and winter. An abrupt increase in the rates of primary production was observed in April-May 2002. Our estimates of photosynthetic parameters coincided with high surface irradiance values (>1000 μmol photons m^{-2} s^{-1}) and elevated chlorophyll *a* concentrations in the range of 5-12 mg m^{-3} throughout the euphotic zone resulting in these elevated production rates (Figure 19). Measurements of primary production at 10m and integrated production estimates have increased from the start of the time series. This increased productivity may account for the observed increase in phytoplankton biomass during this time period. We are currently investigating the relationship between phytoplankton biomass with meteorological, solar radiation, and nutrient inventories to assist our interprertation of the seasonal production dynamics at the fixed coastal station.

Oceanographic Sections – Seasonal and interannual variability in water column optics

Seasonal and spatial variability in the vertical attenuation coefficient was observed along oceanographic sections in 2002 (Figure 20). The spring period showed the highest attenuation as expected, being influenced by the production cycle. Regional differences were apparent in the vertical attenuation coefficient, with the southerly sections (southeast Grand Banks) showing higher extinction of light compared to northerly sections (Bonavista Bay) during the spring. In general, higher attenuation values were observed along the inshore stations and near slope water regions during spring, and remained at background levels of ca. 0.05 during the summer and fall across the Shelf along all sections, with the exception of the Seal Island section (Figure 20). The depth of the euphotic zone (depth of 1 % PAR) determined from the vertical attenuation coefficent, deepened gradually from southern to northern sections along the expected gradient in the production cycle during spring (Figure 21). Values during the spring varied from ca. 20-40m, compared to ca. 60-90m during the summer and fall occupations. The Seal Island section, only occupied during summer, was an exception to this general pattern, in which the euphotic zone extended to shallower depths (Figure 21). The trend in percent change of the attenuation coefficient in 2002 compared to earlier years was negative across different oceanographic sections and seasons, with the exception of the spring occupations for the southeast Grand Banks, and Flemish Cap, and summer occupations for Bonavista Bay and Seal Island (Figure 22). This negative trend would allow higher penetration of incident solar radiation. In contrast, the percent change in the euphotic zone showed a positive trend in 2002 with deeper depths due to lower extinction of light (Figure 22).

Oceanographic Sections - Seasonal and interannual variability in physical structure

Indices of physical structure, including stratification and integrated temperature in the upper 50m, varied by season and location across the oceanographic sections in 2002. Stratification was typically low during the spring and fall periods with values <0.02 Kg m^{-4} along the sections (Figure 23). Water column stability was maximal during summer with values approaching 0.07 Kg m^{-4}, and evidence of a latitudinal gradient in stratification was observed from the Flemish Cap to the northern-most Seal Island section. The stability of the water column also displayed a cross-Shelf gradient during the summer and fallwith higher stratification along the inshore stations and lower values near the slope water regions (Figure 23). The thermal conditions in the upper mixed layer (<50m) during spring 2002 were <0 ^{o}C over much of the inner and mid-Shelf regions, in contrast to the warmer conditions along the outer Shelf being influenced by the North Atlantic Slope waters (Figure 24). The thermal cross-Shelf gradient was still evident during the later occupations in summer and fall across all sections. Both the stratification index and integrated temperature indices revealed large negative percent changes in 2002 compared to earlier years across all sections and seasons (Figure 25). The only exception occurred during spring and summer on the southeast Grand Banks and Seal Island sections respectively.

Oceanographic Sections - Seasonal Variability in Limiting Nutrients

Distribution of silicate and nitrate, the primary limiting nutrients influencing phytoplankton growth, have varied seasonally and spatially across the standard AZMP oceanographic sections since the inception of the program. Depletion of both silicate and nitrate concentrations in the upper water column (< 50m) was evident in the Avalon Channel and Shelf along the southeast Grand Banks and Flemish Cap sections during occupations in spring 2002, in contrast to more replete conditions throughout the upper water column for the Bonavista Bay section (Figure 26). Areas of depleted nutrients coincided with biological consumption inferred from the distribution of chlorophyll a. The location of the offshore branch of the Labrador Current and slope water regions were characterized by upwelling and elevated concentrations of silicate and nitrate along all sections (Figure 26). The distribution of major nutrient concentrations observed in 2002 were similar to the pattern in earlier years.

The depth of depletion of both silicate and nitrate concentrations extended across the entire sections, but varied in the extent of depth by location of the section in summer 2002. The largest vertical removal of major nutrients (<1 mmol m^{-3}) occurred along the Flemish Cap extending to depths of ca. 50m (Figure 27). The vertical extent of nutrient depletion was lower along the Bonavista Bay (at ca. 20-30m) and Seal Island (at ca. 10-20m) sections. Evidence of autumn mixing was evident in the fall period in 2002 with concentrations of silicate and nitrate typically above 1 mmol m^{-3} across all sections (Figure 28).

Seasonal and spatial differences in major nutrient inventories in the upper 50m and deeper layers (50-150m) were evident along the oceanographic sections in 2002. Silicate inventories in the upper 50m were lower along the southerly section and tended to increase northward during the spring occupations. This is likely related to the difference in timing of biological consumption of this limiting nutrient by Diatoms during the spring bloom (Figure 29). Near surface depletion of silicate inventories was evident along the Flemish Cap section during summer, but not observed for sections further north. Upper 50m silicate inventories in the fall indicated extensive mixing along the southeast Grand Banks and Flemish Cap sections, but was more limited along the Bonavista Bay section (Figure 29). Seasonal and spatial variability in nitrate inventories in the upper 50m were coupled with the observed pattern for silicate (Figure 30). Nitrate inventories were slightly lower compared to silicate levels over the inner and mid-Shelf for the Seal Island and Bonavista Bay sections during the spring and summer. Cross-Shelf gradients in silicate and nitrate inventories were evident for the Flemish Cap and

Bonavista Bay sections during spring and fall with higher levels observed along the outer Shelf and across the Cap.

The deep (50-150m) inventories of major nutrients along the inner and mid-Shelf showed substantially lower levels in contrast to the outer Shelf region, during all seasonal occupations for the southeast Grand Banks and Flemish Cap sections (Figure 31, 32). Depletion of these nutrient inventories, can be attributed to the shallow nature of the Shelf (bottom depth typically <100m) in these locations. Deep inventories of major nutrients remained relatively stable seasonally with the exception of silicate levels along the mid to outer Shelf of the Bonavista Bay section during the fall which were approximately one-half of the levels during the spring-summer period.

The percent change in the upper 50m nutrient inventories in 2002 indicated substantially higher levels for both silicate and nitrate across all oceanographic sections compared to earlier years (Figure 33). The elevated levels of these major nutrients in 2002 were greatest during the spring and fall occupations across most sections. The percent change in deep inventories for both nutrients also showed higher levels along the southeast Grand Banks section during spring and fall occupations and likely contributed to the enhanced levels observed in the upper water column through mixing processes. This same explanation did not apply to the other sections which either showed small positive or negative trends in the deep inventories in 2002 compared to earlier years (Figure 33). Small differences in timing between surveys conducted annually during 2000-02 and changes in the production cycle may contribute to the observed patterns in nutrient dynamics.

Oceanographic Sections - Seasonal and interannual variability in Phytoplankton Abundance and Biomass

Distribution of phytoplankton biomass, inferred from the concentration of chlorophyll *a* and consumption of primary nutrients, showed both wide-spread and smaller discrete patches during the seasonal occupations across the standard sections. The southeast Grand Banks was characterized by high chlorophyll *a* concentrations during spring 2002 across the entire Shelf out to the Slope waters and extending to depths of 100m (Figure 26). During this time, the chlorophyll *a* distributions along the Flemish Cap and Bonavista Bay sections were more localized, showing patches of elevated concentrations across the sections. The summer 2002 concentrations of chlorophyll *a* were substantially lower across the Flemish Cap section showing no evidence of episodic or localized blooms, which were mainly confined along the outer Shelf for the Bonavista Bay and cross-Shelf for the Seal Island sections (Figure 27). In contrast to previous years, chlorophyll *a* concentrations were low (< 1mg m^{-3}) across all sections in fall 2002 (Figure 28).

Chlorophyll *a* inventories in the upper 100m followed the expected seasonal pattern, reaching levels > 100 mg m^{-2} (i.e., bloom criteria) only during the spring period (Figure 34). In addition, cross-Shelf gradients in chlorophyll *a* concentration were observed along the southeast Grand Banks and Flemish Cap sections during spring. The later seasons showed little variability across the Shelf and low integrated chlorophyll *a* concentrations, typically < 50 mg m^{-2}. The percent change in chlorophyll *a* inventories in 2002 was largely negative compared to earlier years across all sections (Figure 35). The exception to this pattern occurred during the spring occupation of the southeast Grand Bank section which displayed the only positive trend in 2002 compared to earlier years.

Diatom and Flagellate taxa showed elevated cell densities up to 10^5-10^6 cells L^{-1}, while Dinoflagellate concentrations were lower from 10^3-10^4 cells L^{-1} (Figure 36). All phytoplankton taxa were widely distributed across the southeast and northeast Newfoundland Shelf and comparisons with abundance at Station 27 were in general agreement during spring occupations. During the summer occupations, Diatoms were largely absent from the Newfoundland Shelf and only occurred in high densities along the Labrador Shelf, consistent with the delay in timing of the production cycle observed in earlier years (Figure 37). The abundance of Dinoflagellates were somewhat higher, in contrast to lower concentrations of Flagellates, but both taxa were still widely distributed across the Shelf and Slope regions during this period. During the fall occupations, abundance and distribution patterns were similar to the summer period (Figure 38).

Satellite Imagery

Time series of bi-weekly surface chlorophyll *a* concentrations from the Newfoundland and Labrador sub-regions showed a regular seasonal bimodal pattern with a dominant periodicity during the spring and fall across all areas (Figure 39). The annual surface chlorophyll *a* concentrations across the Newfoundland and Labrador sub-regions varied little during the available time series from 1998-2002 (Figure 40). The satellite remote sensing information provides the ability to investigate the timing of peak concentrations of chlorophyll associated with the production cycle. The timing of the peak surface concentrations varied with location of the SeaWiFS sub-region (Figure 40). Peak surface chlorophyll *a* concentrations occurred later (late May-June) on the northern and southern Labrador Shelf, compared to late March-April on the southern Newfoundland Shelf. The timing of peak surface blooms suggested the late 90's was characterized by an earlier production cycle compared to current conditions, particularly along the southern and northeast Newfoundland Shelf, consistent with the warming trend observed in ocean temperatures since 1996 (Colbourne 2002).

In all instances there may be subsurface concentrations of chlorophyll *a* that can not be detected from sea surface observation using satellite ocean colour sensors. However, the general correspondence between our discrete measurements with the ocean colour data suggests that the general interannual trends in the timing of the production cycle may be well represented by remotely sensed data.

Fixed Station - Zooplankton

Since 1999, the general pattern of seasonality in overall zooplankton abundance at Station 27 has been low numbers of organisms at the start of the year with the highest abundance occurring in late fall (Figure 41). In 2002, the overall abundance of zooplankton was comparable to levels observed in the three previous years but the seasonality was markedly reduced because of high numbers of zooplankton present in the late fall of 2001 and early winter of 2002. The increased abundance during the winter was due to higher numbers of *Oithona* sp. and *Pseudocalanus* sp. copepodites than had been previously observed at this site. Because of the high abundance of small copepods during the early part of the year, the relative contribution of *Calanus finmarchicus* to the zooplankton community appeared to be somewhat reduced although the number of late stage copepodites were similar to previous years (see below). The greatest changes in zooplankton community structure since 1999 has been the growing frequency of occurrence and relative abundance of *C. glacialis* and *C. hyperboreus* as well as *Microcalanus* sp. during the late spring and early summer and the gradual decrease in relative occurrence and abundance of *Temora longicornis* (Figures 41, 42). Although the overall abundance levels of these species appear to be in line with previous observations, the principle difference has been in the occurrence of the four taxa, with cold water species appearing more consistently throughout the year while the warmer water *T. longicornis* appears less frequently. These changes resulted in a decrease in the relative abundance of *Oithona* sp. and *Pseudocalanus* sp. during the summer months relative to the three previous years. The other major zooplankton taxa showed no little change in overall or relative abundance (Figure 42).

The overall abundance of *C. finmarchicus* at Station 27 was comparable to previous years although somewhat lower than concentrations observed in 1999 (Figure 43). In contrast to 2001, the seasonal succession of copepodite stages did not show a delay, with the CI stages beginning to appear in large numbers by the end of May. This return to the pattern of succession found in 1999/2000 relative to 2001 when the spring bloom was delayed suggests that the onset of the spring bloom may play an important role in the seasonal development of cohorts for this species. However, in contrast with previous years, early stage copepodites were effectively absent from the zooplankton community by the end of August whereas there has normally been low numbers occurring throughout the fall. Furthermore, there appears to have been very few CVI adults at Station 27 after the end of July, in contrast to 1999 and 2001 when adult copepodites occurred frequently at the fixed station.

The overall abundance of *Pseudocalanus* sp. did not show as marked a seasonality as in previous years during the January to March period (Figure 44). This did not appear to be due to a marked difference in the stage composition of this species during late 2001/early 2002. However, later in 2002, the development of the summer cohort of *Pseudocalanus* sp. appeared to be delayed, with the peak in the relative abundance of CV stages occurring approximately 1 month later than in the three previous years. Furthermore, the relative abundance of copepodites after August was notably more important than in previous years.

Oceanographic Sections - Zooplankton

Total zooplankton abundance in the fall of 2001 was generally higher than in the previous two years (Figure 45). The largest concentrations occurred in the offshore areas of the Bonavista and Southeast Grand Banks sections where higher abundances were notable across most of the Flemish Cap section. In general, the higher abundance of zooplankton was due principally to larger overall abundance of *Oithona* sp., as observed at Station 27. Further offshore, along the continental slope, the abundance of *C. finmarchicus* was often enhanced by 2-4 fold over previous years. In the area of the Flemish Pass, a few stations had high abundances of *Fritillaria borealis* and *Oikopluera* sp., two larvacean species, as well as high abundances of bivalve larvae and pelagic gastropods. *Oithona* sp. was the dominant copepod across all sections, ranging from ~40-80% of all copepods, even in offshore areas (Figure 46). *Pseudocalanus* sp. was present only in the Shelf areas and was absent from stations located in slope waters. The relative abundance of *C. finmarchicus* was greatest in offshore areas but notable abundances were found across the entire Bonavista Bay section and in the Avalon Channel along the Flemish Cap and Southeast Grand Banks sections.

During the spring of 2002, the overall abundance of zooplankton was often 3 to 10 fold lower than in 2000 but generally comparable to levels observed in 2001 (Figure 47). The greatest differences occurred on the Southeast Shoal where overall abundance of calanoid nauplii, *Oithona* sp., *Pseucalanus* sp. and larvaceans were generally lower than observations from the survey in 2000. Furthermore, there were high abundances of *T. longicornis* in 2000 which were ~10 times less abundant in 2001 and 2002. Across most of the Flemish Cap section, abundance levels were comparable to those observed in previous years. However, higher abundances were observed at a few stations along the Flemish Cap section where high numbers of bivalve larvae and pelagic gastropods contributed to the overall increase in abundance. Abundance levels were also low in the offshore portion of the Bonavista Bay section, where numbers of calanoid nauplii, *C. finmarchicus*, *Oithona* sp. and *Pseudocalanus* sp. were generally lower than in previous years. The lower abundance of these major groups of copepods resulted in an apparent increase in the relative importance of other taxa, such as *C. glacialis* and *C. hyperboreus* as well as *Metridia* sp., which were found at abundance levels comparable to previous years (Figure 48). In offshore areas, *C. finmarchicus* was an important component of the copepod community, making up ~20-50% of the overall number of individuals. Large calanoid nauplii and *Pseudocalanus* sp.were relatively more abundant on the Shelf rather than in offshore areas (Figure 48).

During the summer 2002 surveys, the overall abundance of zooplankton was generally comparable to levels observed in previous years (Figure 49). There were a few instances along the Flemish Cap section where the abundance in 2001 was substantially higher than in 2002 but in general these were single instances of a high catch for a single species. There was a more consistent difference along the outer portions of the Bonavista Bay section and across the entire Seal Island section where the overall abundance of zooplankton was 2-4 times higher in 2002 than in previous years. In general, the increase was due to greater numbers of *C. finmarchicus*, *Metridia* sp., and large calanoid nauplii. However, the overall zooplankton abundance along the Makkovik Bank section was similar to that found in previous years. Along the Flemish Cap and Bonavista Bay sections, there was a notable increase in the relative abundance of *Metridia* sp. and *C. glacialis* copepodites (Figure 50). However, the relative abundance of these species was normal along the Makkovik Bank section whereas *Pseudocalanus* sp. was particularly abundance near the coast. There was a increase in the relative abundance of calanoid nauplii along the Seal Island and Bonavista sections but a corresponding decrease along the Flemish Cap transect. The overall abundance of both *C. finmarchicus*, *C. glacialis* and *Metridia* sp. was generally higher than in previous years as was the abundance of *Microcalanus* sp. in offshore areas (their abundance on the Shelf was at comparable densities to previous observations).

Discussion

The seasonality of chemical and biological variables at Station 27 and along the major AZMP sections was similar to previous years (1999-2001). The timing of events on the Newfoundland Shelf (south of Seal Island) was once again similar to conditions observed in the early part of the AZMP but in contrast to 2001 when the onset of the spring phytoplankton bloom was delayed. However, satellite information indicates that the relative delay in the onset of the spring bloom remained as one moved further north.

It is becoming clear that interannual variations in the seasonality of vertical mixing and water column structure plays an important role in the seasonal phytoplankton cycle along the Newfoundland Shelf. In 2001, the delay in the onset of the spring bloom was associated with persistent deep mixing of the water column. Although wind stress remained high in 2002, the overall impact on the water column may have been somewhat lessened by the relative timing and intensity of wind events such that the mixed layer depth shoaled more progressively in 2002, thus allowing an earlier spring bloom.

Variations in the physical environment since the inception of the AZMP may also be contributing to a gradual increase in the magnitude of the spring phytoplankton bloom. Since 2000, there has been a gradual intensification in the overall productivity and standing stock of phytoplankton during the spring. The gradual rather than abrupt shoaling of the mixed layer may have provided sufficient light and high nutrient availability to permit the development of denser phytoplankton population, mainly composed of diatoms, than in previous years. However, in addition to the factors that regulate the vertical structure of the water column, there is a preliminary indication that interannual variations in incident light may also have contributed to the increase in the overall intensity of the spring phytoplankton bloom. Although intercalibration of observations from the Northwest Atlantic Fisheries Centre with those collected by the Canadian Meteorological Service has yet to be completed, the first indications are that incident radiation in 2001 and 2002 are at the upper extreme of light levels observed in the past three decades at St. John's airport.

In 2001, the deep nutrient inventories (> 50m) observed at Station 27 showed a 30-50% decrease over conditions in previous years but the change was not observed along any of the standard sections. The condition at Station 27 persisted in 2002 but there are some indications that the depletion of the deep nutrient pool may have expanded onto the inshore and mid-Shelf portions of the Bonavista Bay section, where a notable decrease in deep nutrient levels were observed in 2002, but the magnitude is considerably less than has been observed at Station 27 (seasonally averaged decrease of 10% versus 30% over the 2000-01 period).

The relationship between silicate and nitrate concentrations in the upper layer (0-50 m) indicates that both nutrients are taken up by the phytoplankton community. During much of the year, nitrate appears to have a greater potential to limit phytoplankton production. However, there is also an indication that replenishment of silicate is more extensive than that of nitrate throughout much of the year.

The overall standing stock of phytoplankton on the NE Newfoundland Shelf was generally less during the summer and fall surveys than in previous years. Although stratification was less intense, which suggests that nutrient replenishment may have occurred more readily, the integrated temperature was also lower, suggesting that decreases in temperature may play an important role in limiting production on the Shelf. Alternatively, higher grazing pressure from a slight increase in the density of large calanoid copepods may have maintained standing stocks at low levels.

The decrease in the relative importance of Flagellates in the overall composition of the phytoplankton community observed in 2001 appears to have persisted into 2002. Although these organisms do not make up a substantial portion of the overall phytoplankton biomass, the decrease in their abundance may suggest a change in the dynamics of the microbial food web dynamics in the area. Further investigation is required.

The overall abundance of zooplankton at both Station 27 was generally in keeping with previous observations, with the exception of the fall and winter of 2001/02 when high concentrations of *Oithona* sp. and *Pseudocalanus* sp. were present. The overall increase in overwintering numbers of these two species did not result in a substantial increase in population densities during the subsequent spring and summer at this site, or along the sections further south. The most notable change in the zooplankton community structure at the fixed station has been in the increase in the abundance of cold water species of copepods. Although other taxonomic groups have fluctuated in abundance, copepodites of *Metridia* sp., *C. glacialis*, *C. hyperboreus* and *Microcalanus* sp. have become more frequent members of the community although the overall increase in their abundance has been modest. The warm water species, *T. longicornis*, whose abundance peaks during the fall, has shown a decrease in overall abundance but more importantly the relative frequency of occurrence at Station 27 appears to have decreased since 1999. The change in occurrence of cold and warm water species of copepods is relatively consistent with the changes in water mass characteristics which have taken place since the late 90s.

The greater occurrence and abundance of large species of copepods such as *Calanus* and *Metridia* may have lead to an increase in the relative abundance of large calanoid nauplii on the mid- and outer shelf areas. Although small species of copepods, such as *Oithona* sp. and *Pseudocalanus* sp. still dominate the copepod community across much of the NE Newfoundland Shelf, the increase in the abundance of large species may have lead to an overall increase in the biomass of the zooplankton community, particularly within the core of the Labrador current.

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Table 1. Listing of AZMP sampling surveysin the Newfoundland Region in 2002. The transects are 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); Beachy Island (BI), and the fixed station (Station 27). See Figure 1 for station locations along sections and fixed coastal station. Total numbers of hydrographic (CTD) and biological (nutrients, plant pigments, phytoplankton, and zooplankton) profiles provided for each seasonal section and fixed station occupations.

Mission ID	Dates	Sections/Fixed	# Hydro Stns	# Bio Stns
2002	Apr 20-May 5	SEGB, FC, BB, FI	108	66
2002	Jul 12-Jul 28	FC,BB,FI,WB,SI,MB,BI	109	57
2002	Nov 7-Nov 22	SEGB,FC,BB,S27	92	51
2002	Jan-Dec	Station 27	49	23

Table 2. Average and standard deviation (SD) of daily photosynthetic active radiation (PAR), total monthly radiation in moles and total daily insolation obtained in 2002 from Li-Cor PAR sensor located at NWAFC (47.52 N, 52.78 W), St. John's, Newfoundland.

Month (Julian Day)	**Avg. Daily Moles m^{-2}**	Avg. Daily SD	**Total Moles**	**Total Daily Insolation Moles d^{-1}**
January (1-31)	8.23	4.55	255.23	0.17
February (32-59)	12.96	6.62	362.89	0.30
March (60-90)	19.96	9.10	618.66	0.54
April (91-120)	29.28	10.28	878.31	0.92
May (121-152)	36.52	15.69	1132.22	1.27
June (153-181)	40.23	16.30	1206.77	1.47
July (182-212)	43.58	13.48	1350.87	1.56
August (213-243)	36.22	10.77	1122.86	1.19
September (244-273)	24.98	11.99	749.49	0.72
October (274-304)	16.60	6.41	340.58	0.41
November (305-334)	7.60	4.18	227.92	0.16
December (335-365)	5.95	2.85	184.54	0.12

Figure 1. Station occupations during AZMP Seasonal Sections on the Newfoundland and Labrador Shelf.

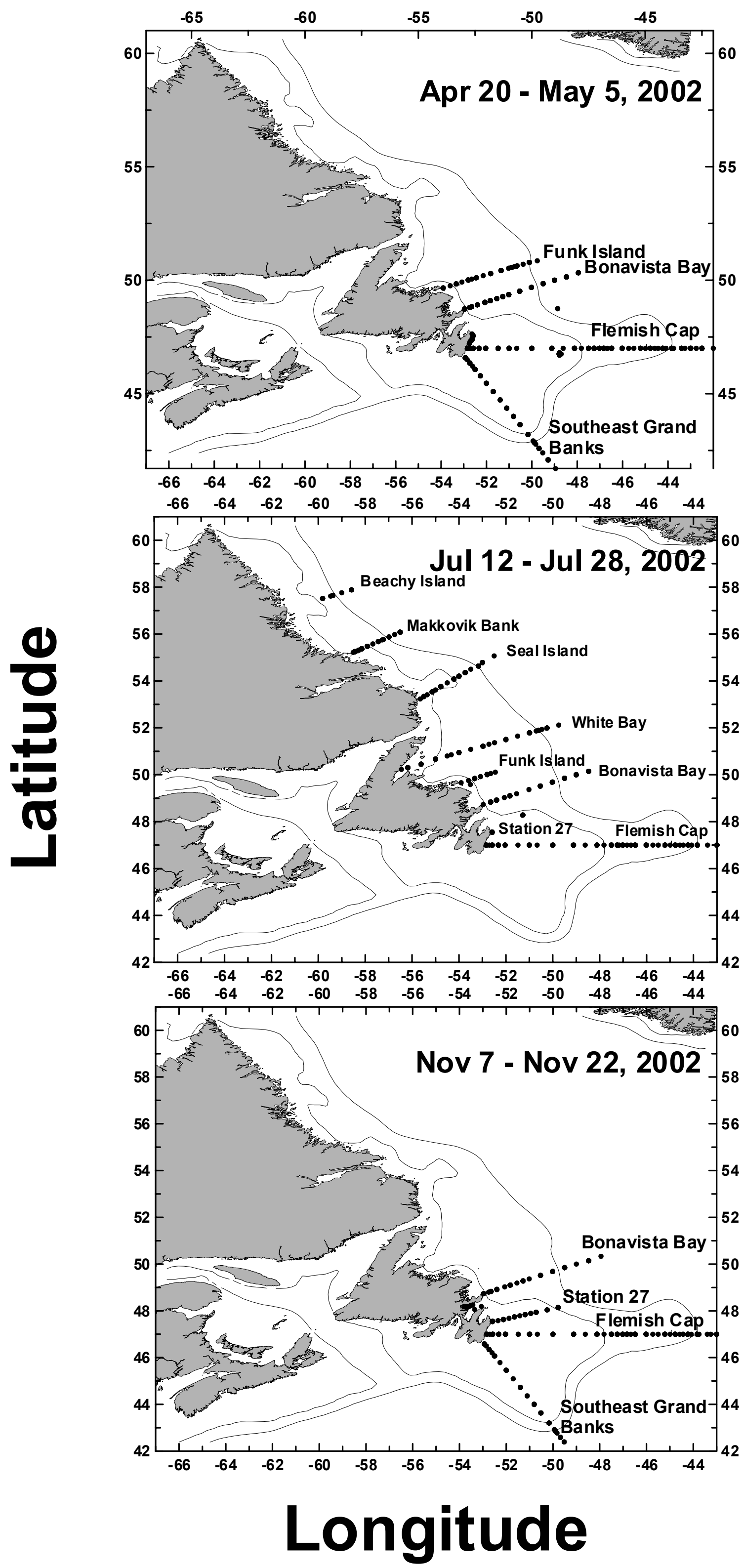

Figure 2. Biweekly time series of optical measures at Station 27 showing vertical attenuation coefficient K_dPAR (estimated from Platt *et al*. 1988 model), euphotic depth (depth of 1 % PAR), and total average daily PAR obtained from Li-Cor (SA-192A) irradiance sensor located at NWAFC, St. John's, NL.

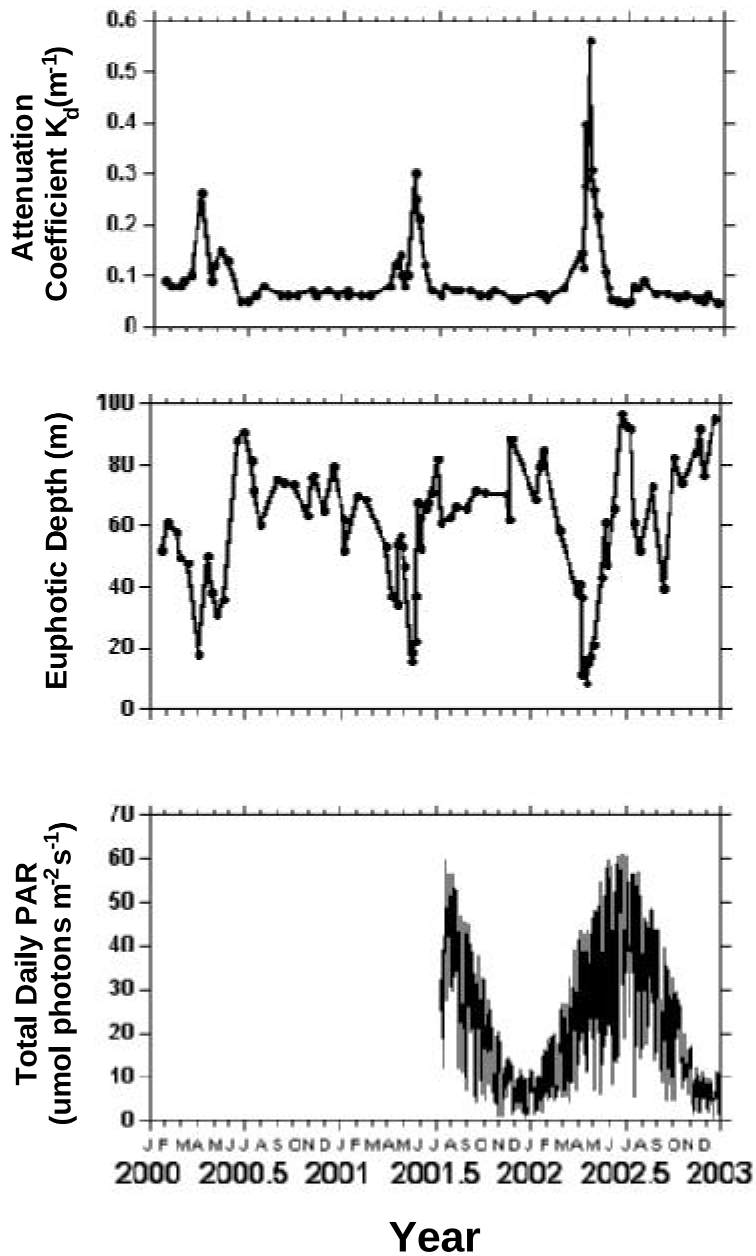

Figure 3. Time series of average monthly values of photosynthetic active radiation (PAR) in St. John's, NL obtained from Environment Canada 1964-1998, and Northwest Atlantic Fisheries Centre 2001-02 (upper panel). Two gaps exist in the current time series; April-August 1997, and January-June 1999-2001. Monthly climatology of PAR showing recent measurements were among the highest recorded during the available time series for months of April through to October (lower panel).

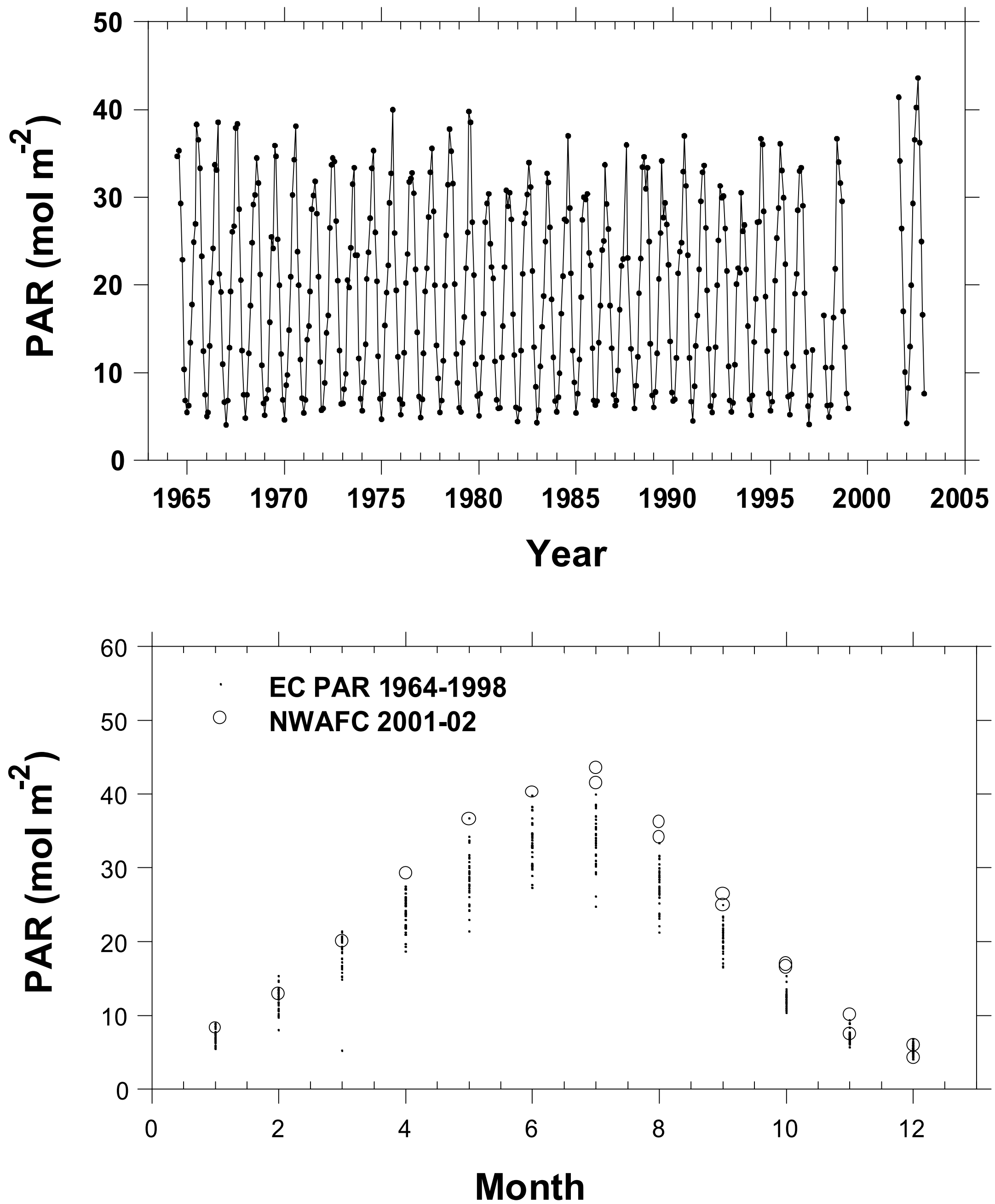

Figure 4. Seasonal variability in vertical attenuation coefficient (estimated from Platt *et al*. 1988 model) and euphotic depth (depth of 1 % PAR) during 2002 at Station 27. Seasons were broken down quarterly as 3inter; Dec-Feb, spring; Mar-May, summer; Jun-Aug, and fall; Sep-Nov.

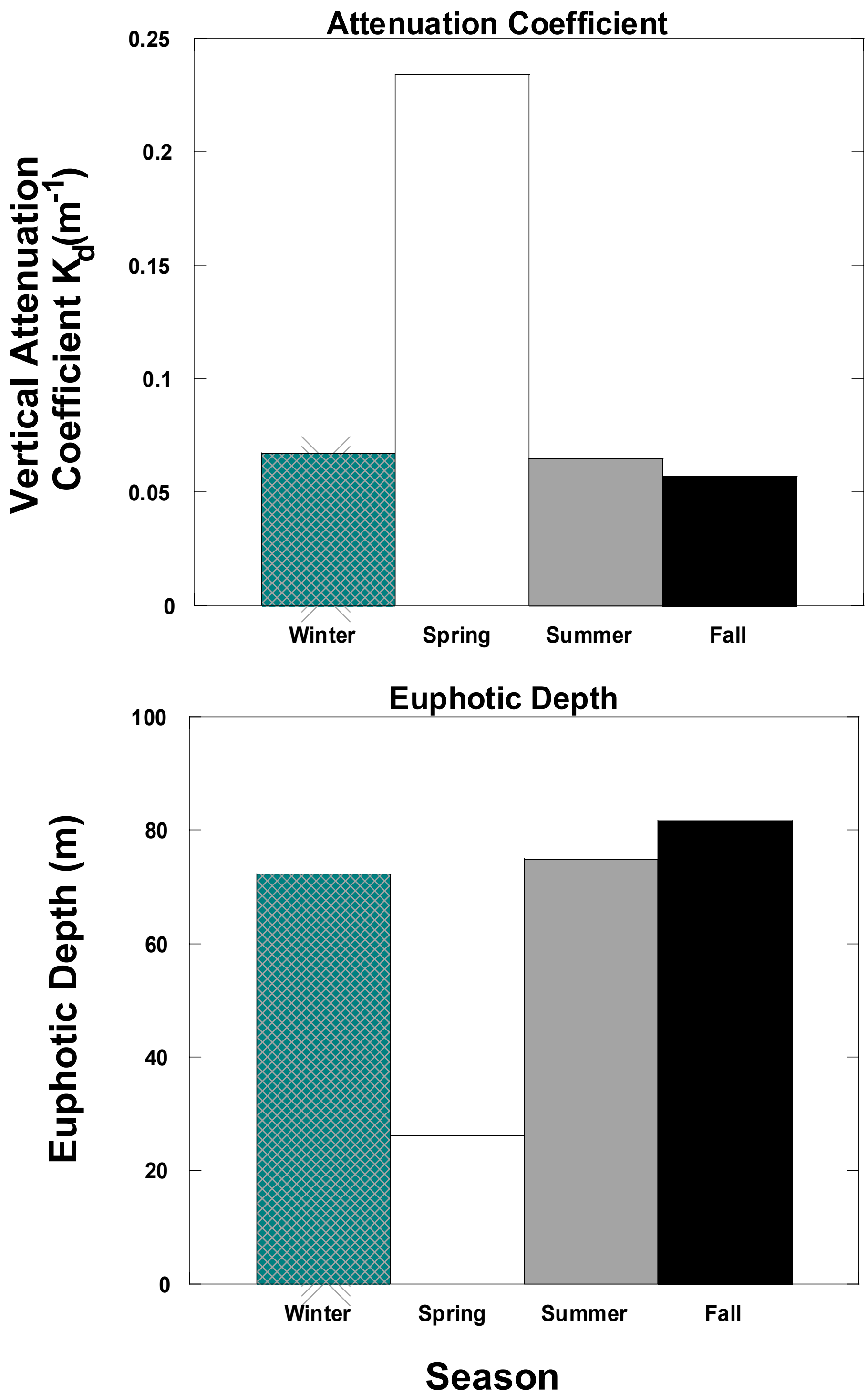

Figure 5. The mean percent change in vertical attenuation coefficient and euphotic depth (1 % light level) in 2002 compared to earlier years (2000-01) at Station 27 during different seasons (winter; Dec-Feb, spring;.Mar-May, summer; Jun-Aug, fall; Sep-Nov).

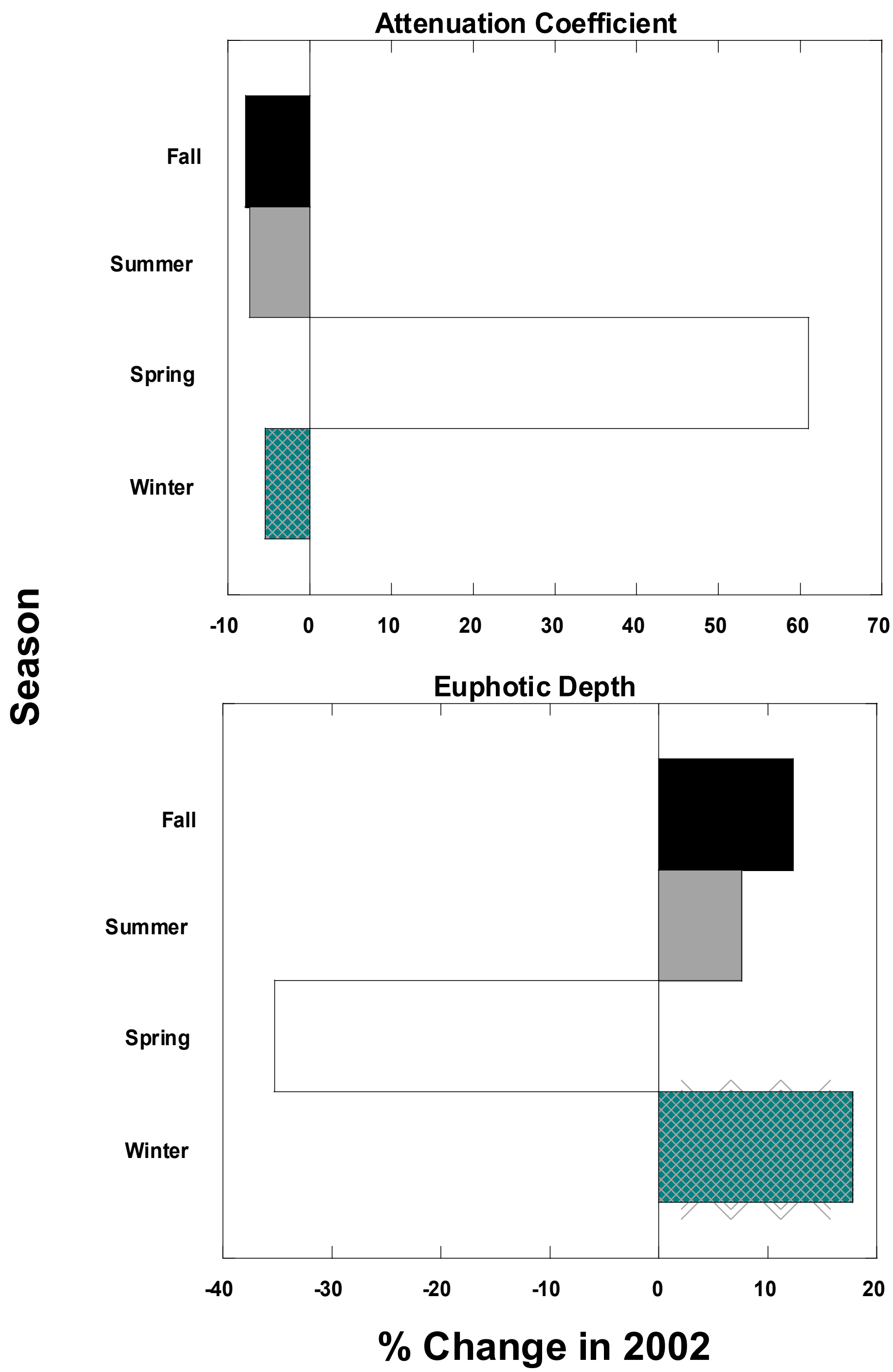

Figure 6. Biweekly time series of physical measures at Station 27 during 2000-02 showing stratification index ((sigma-t 50m – sigma-t 5m)/45m), mixed layer depth (taken as depth centre of pynocline), and integrated temperature in upper 50m using trapezoidal method. Corresponding panel showing average daily (hourly observations) time series of meteorological conditions at a ground station (47.56° N, 57.21° W) in St. John's, Newfoundland, showing atmospheric pressure, wind stress ($0.02*\text{wind speed}^2$, index of wind-induced mixing in upper water column), and air temperature (dry bulb).

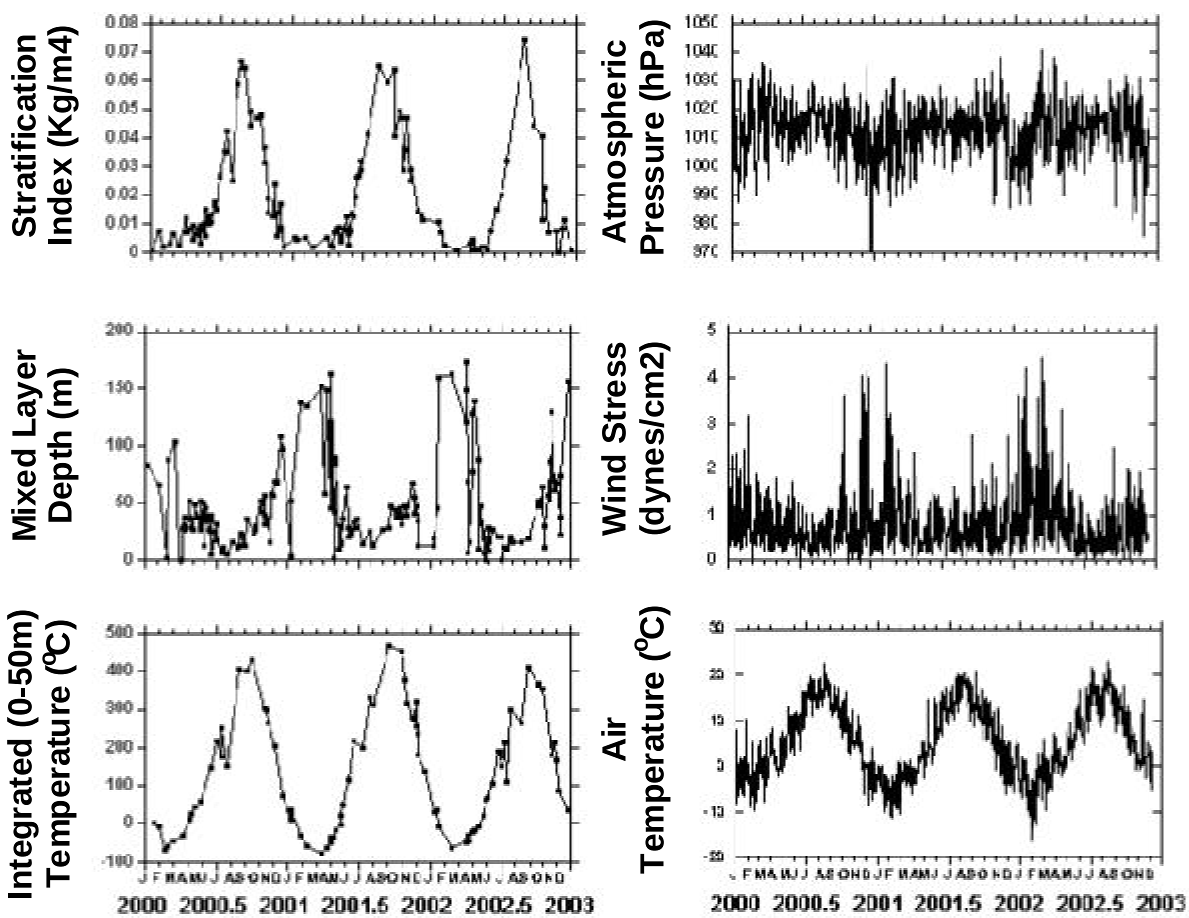

Figure 7. Seasonal variability in stratification index ((Sigma-t 50m – Sigma-t 5m)/45m) and integrated temperature (0-50m integral) during 2002 at Station 27. Seasons were broken down quarterly as winter; Dec-Feb, spring; Mar-May, summer; Jun-Aug, and fall; Sep-Nov.

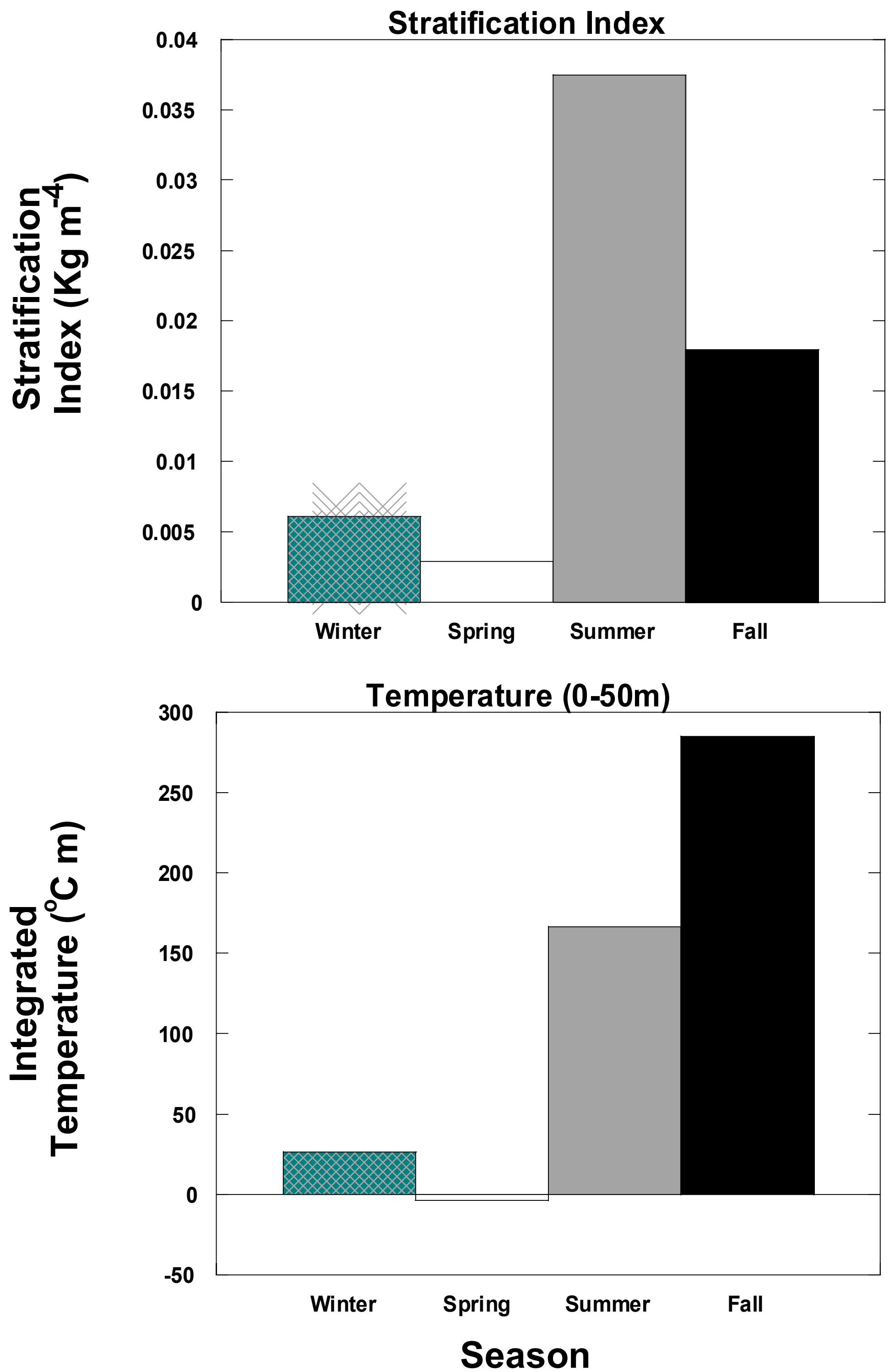

Figure 8. The mean percent change in stratification index (difference between Sigma-t at 50m and 5m) and integrated temperature (0-50m) in 2002 compared to earlier years (2000-01) at Station 27 during different seasons (winter; Dec-Feb, spring; Mar-May, summer; Jun-Aug, fall; Sep-Nov).

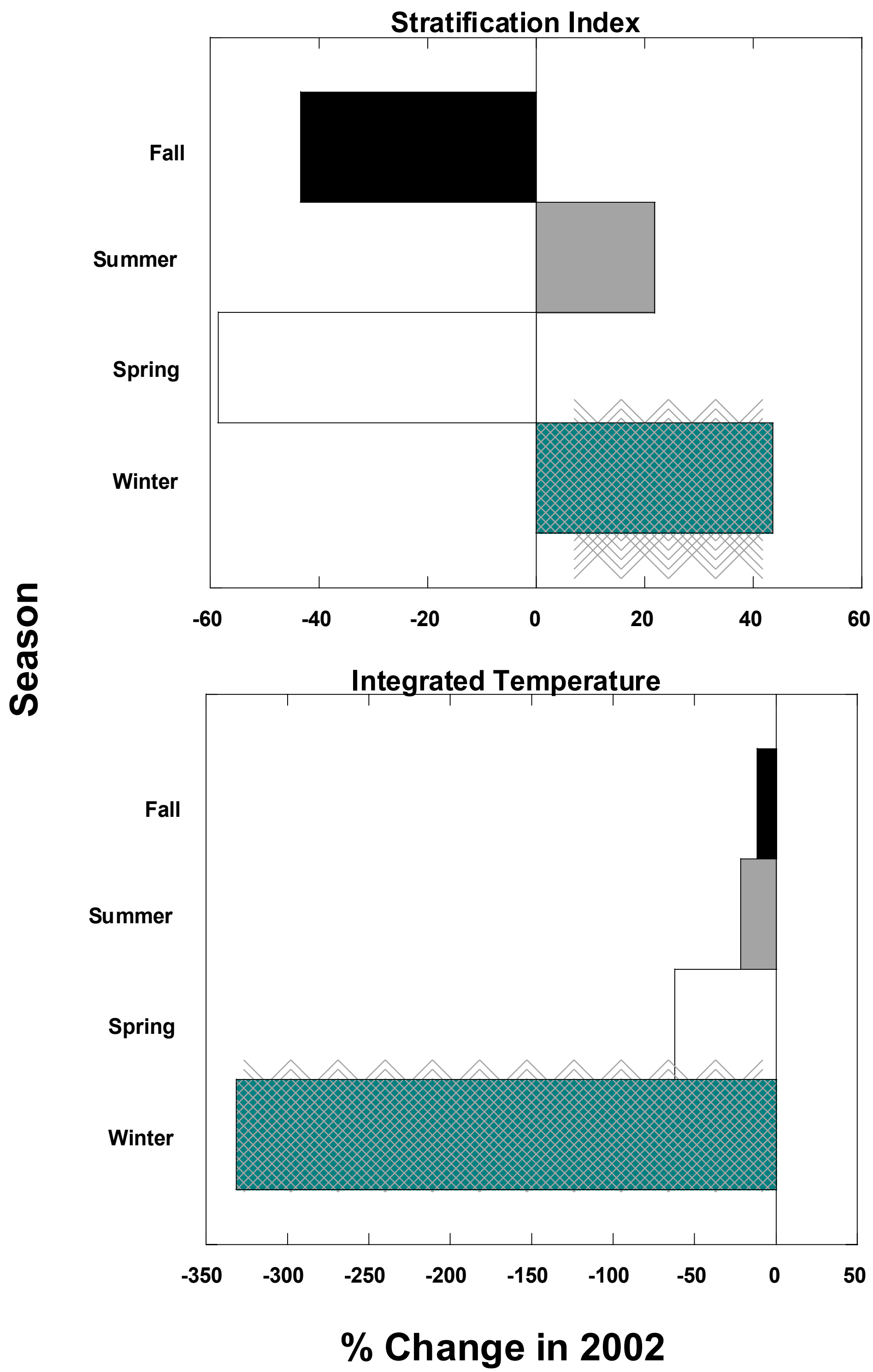

Figure 9. Seasonal variation in vertical structure of silicate and nitrate concentrations at Station 27 during 2000-02.

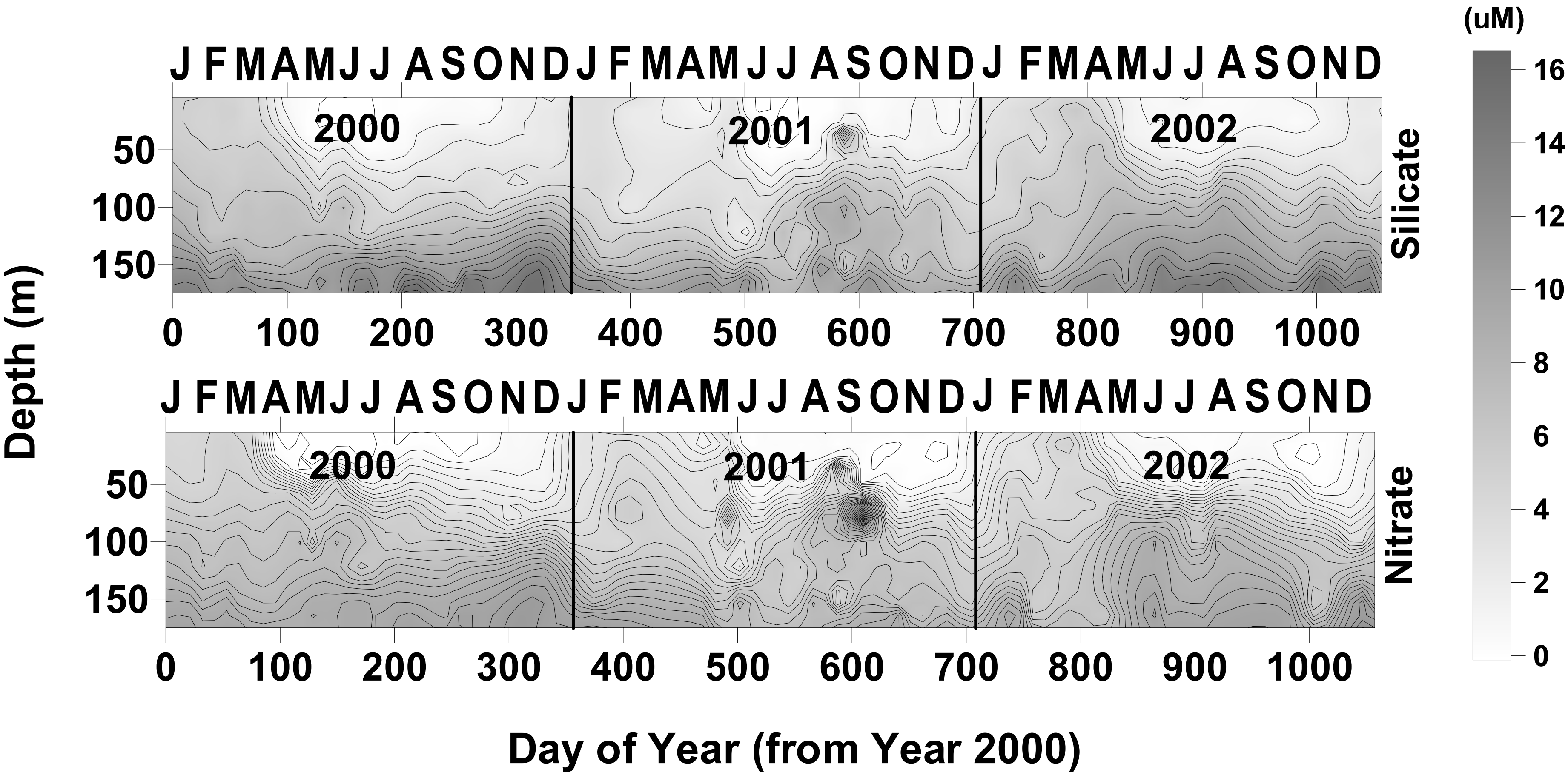

Figure 10. Time series of major nutrient inventories at Station 27 during 2000-02 showing silicate and nitrate at two depth strata.

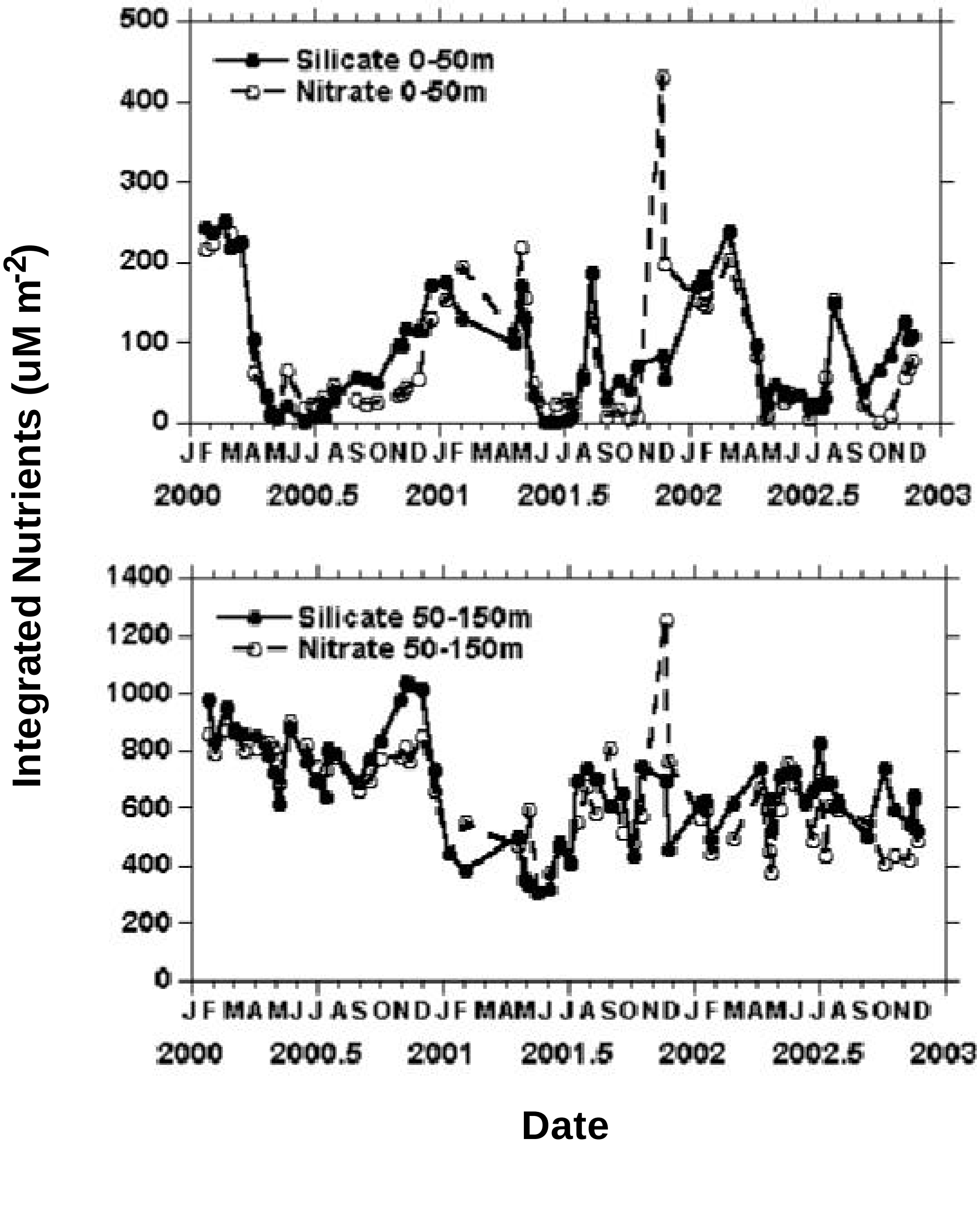

Figure 11. Seasonal variability in nutrient inventories during 2002 at Station 27. Seasons were broken down quarterly as winter; Dec-Feb, spring; Mar-May, summer; Jun-Aug, and fall; Sep-Nov.

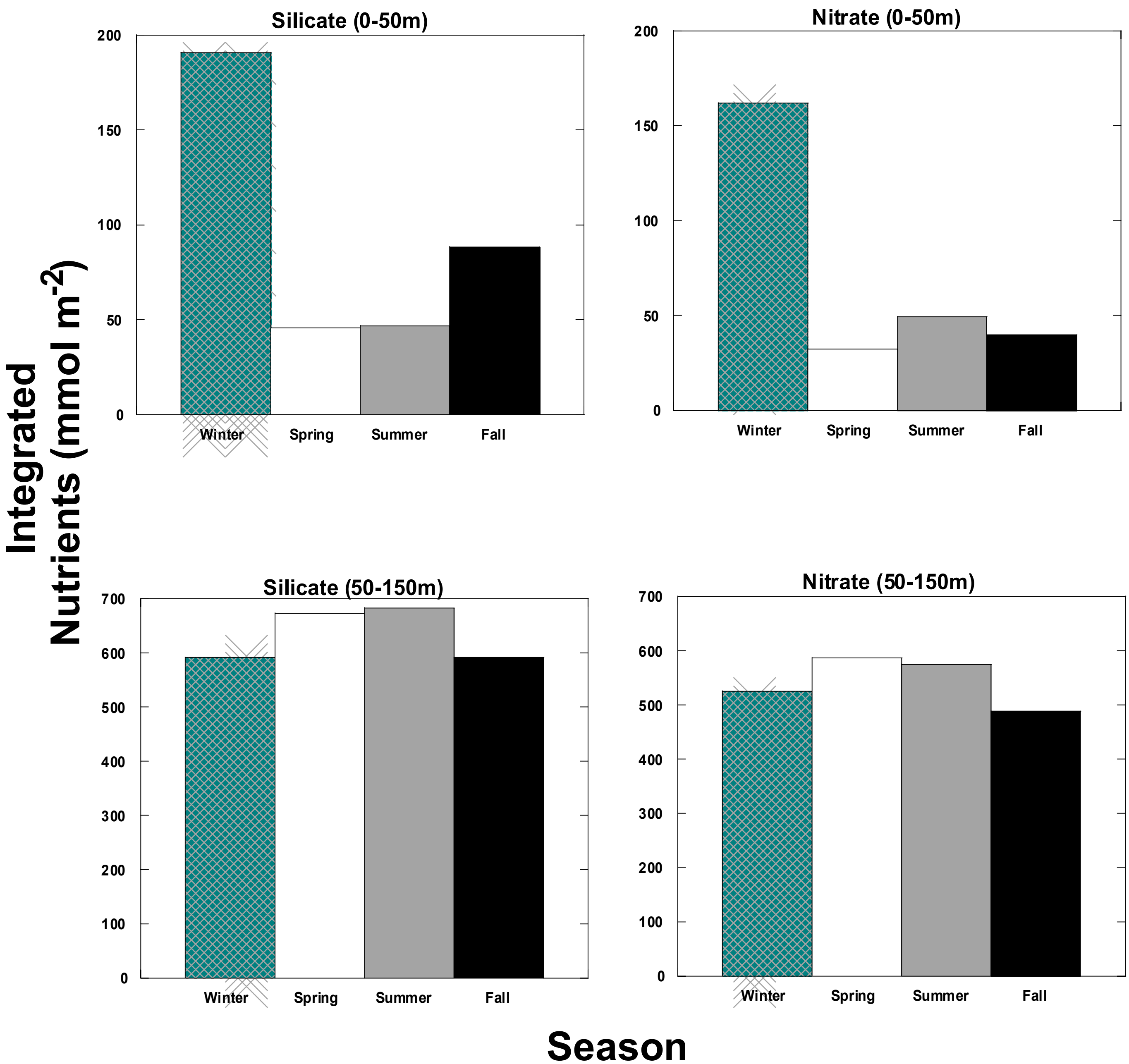

Figure 12. The mean percent change in silicate and nitrate inventories in shallow (0-50m) and deep (50-150m) strata in 2002 compared to earlier years (2000-01) at Station 27 during different seasons (winter; Dec-Feb, spring; Mar-May, summer; Jun-Aug, fall; Sep-Nov).

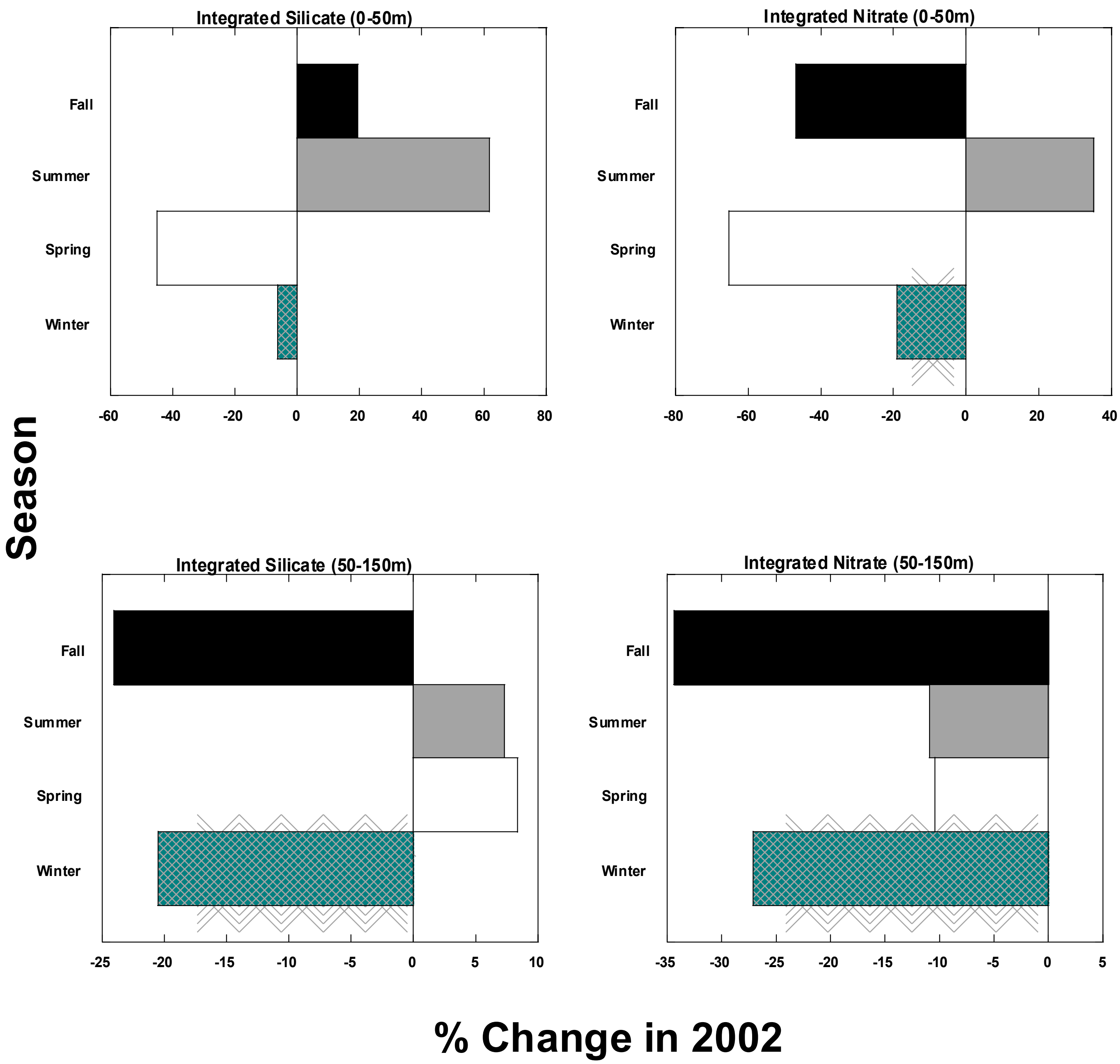

Figure 13. Relationship between silicate and nitrate for seasonal oceanographic sections and Station 27 occupations during 2002. Polynomial regression parameters provided for each seasonal period.

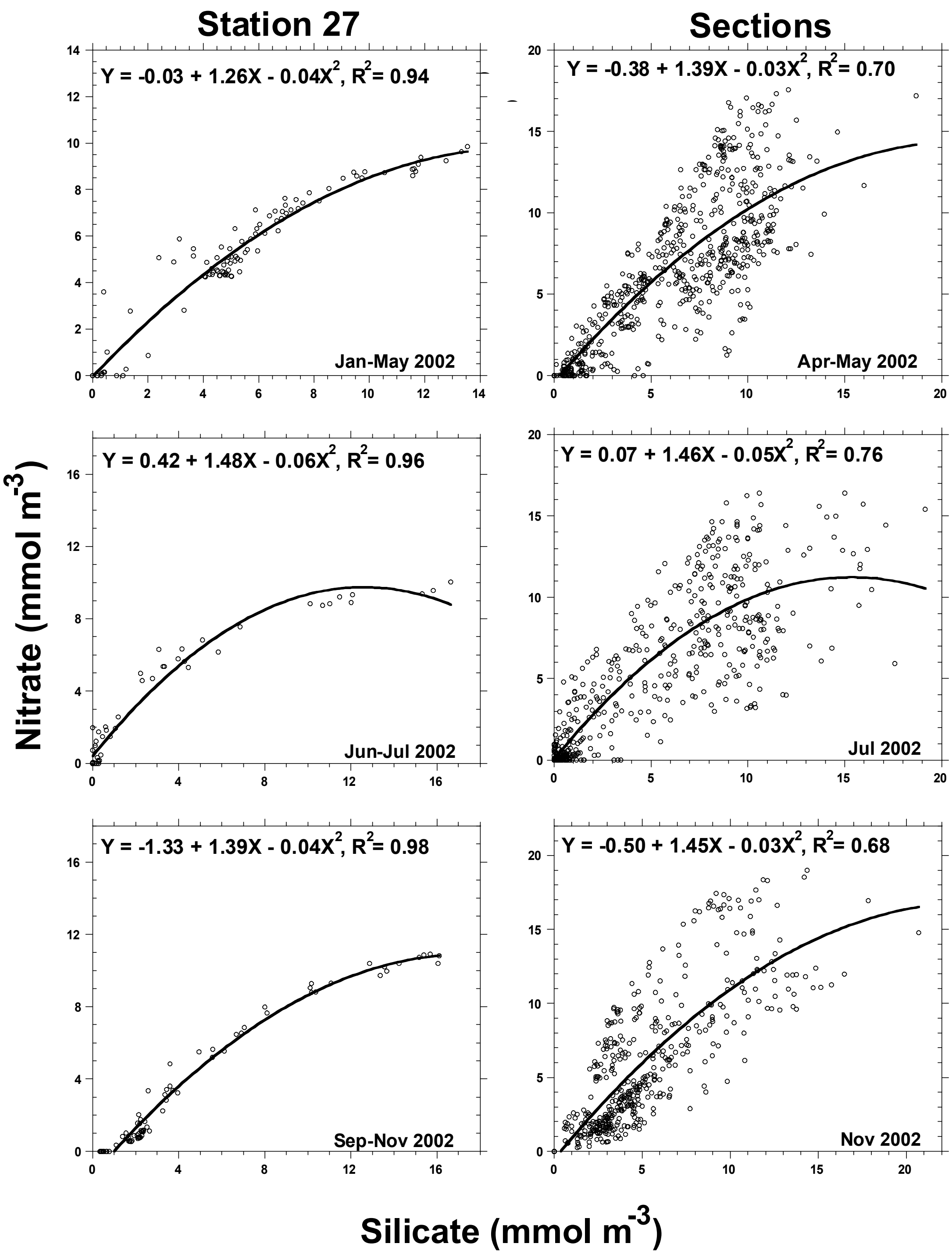

Figure 14. Seasonal variation in vertical structure of chlorophyll a concentration at Station 27 during 2000-02.

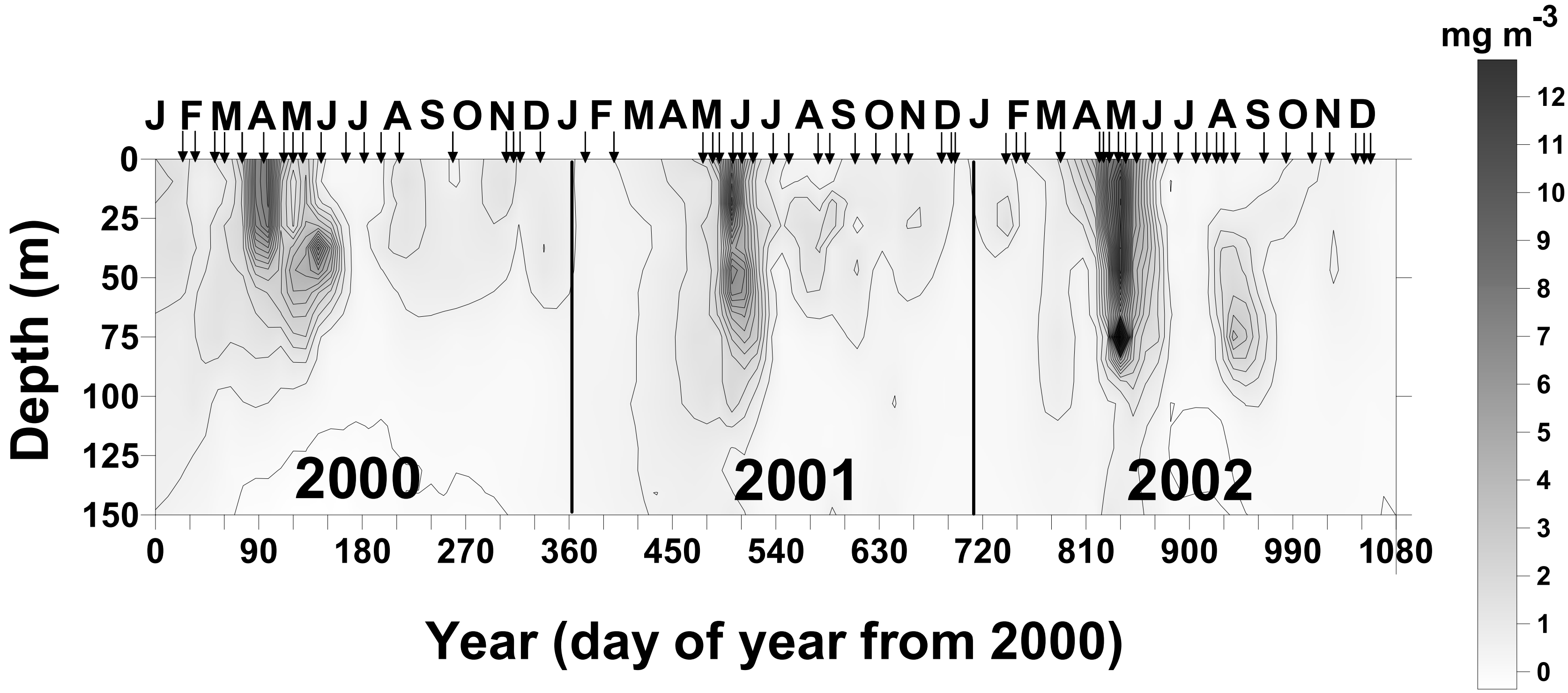

Figure 15. Time series of biological measures at Station 27 during 2000-02 showing inventories of chlorophyll a at two depth strata, *in-situ* chlorophyll a fluorescence (calibrated against extracted chlorophyll a), and estimated parameters derived from shifted Gaussian model fit to extracted chlorophyll a.

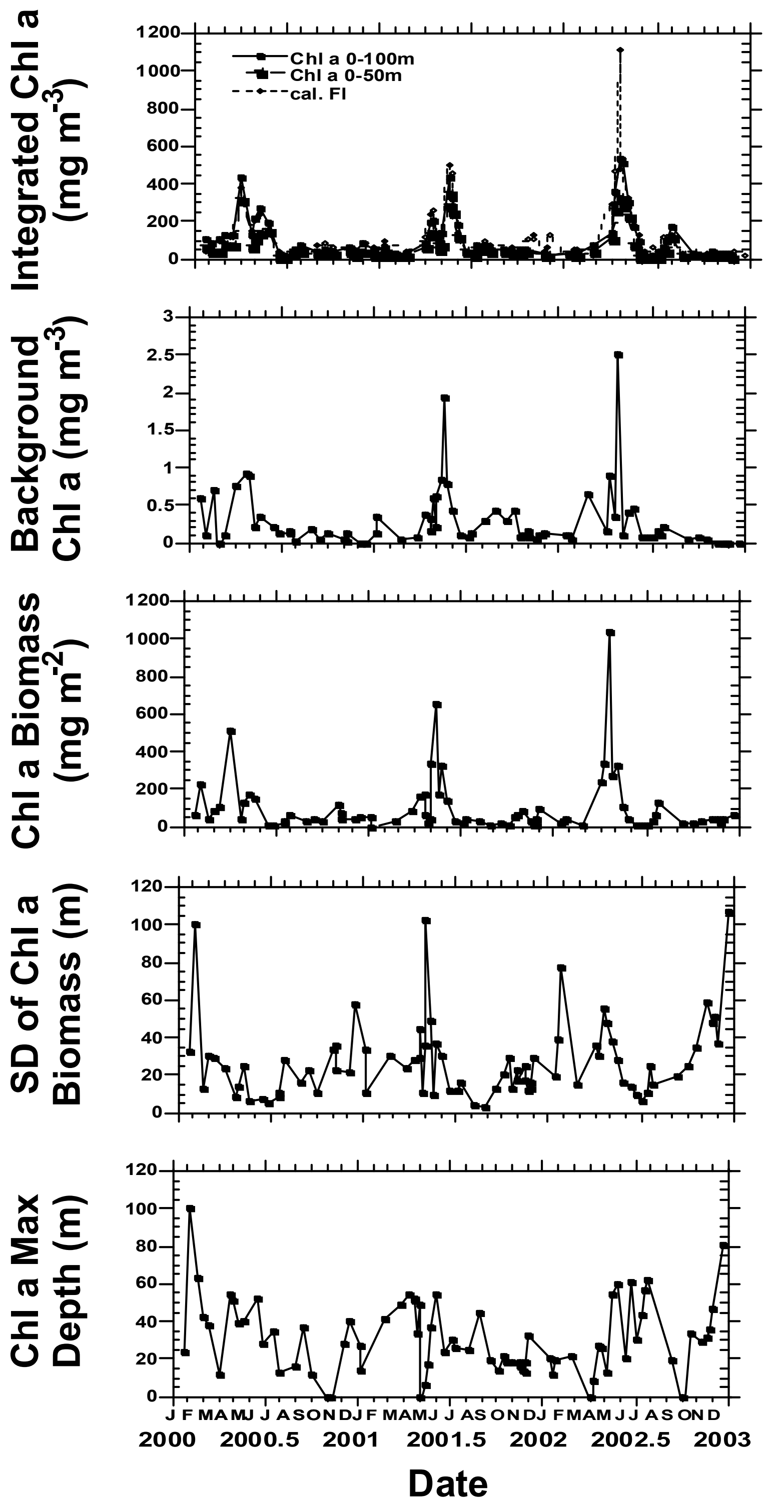

Figure 16. Seasonal variability in chlorophyll a inventory during 2002 at Station 27. Seasons were broken down quarterly as winter; Dec-Feb, spring; Mar-May, summer; Jun-Aug, and fall; Sep-Nov.

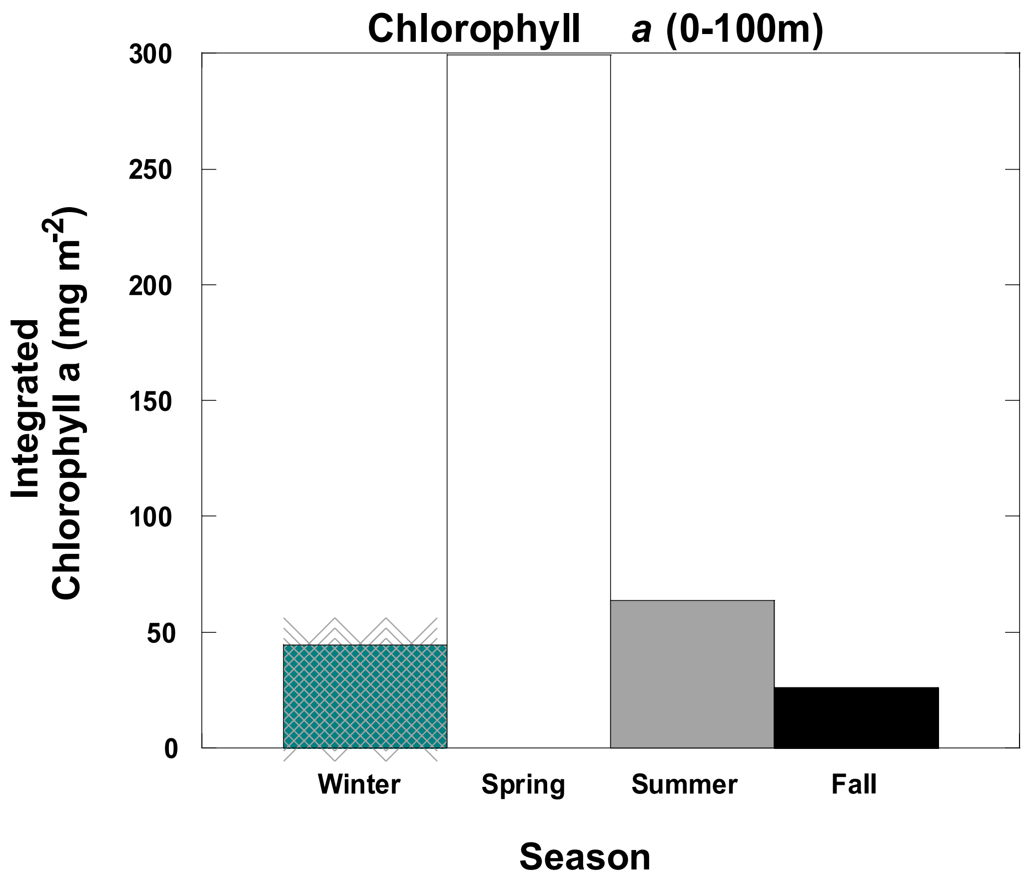

Figure 17. The mean percent change in chlorophyll a inventory (0-100m integral) in 2002 compared to earlier years (2000-01) at Station 27 during different seasons (winter; Dec-Feb, spring; Mar-May, summer; Jun-Aug, fall; Sep-Nov).

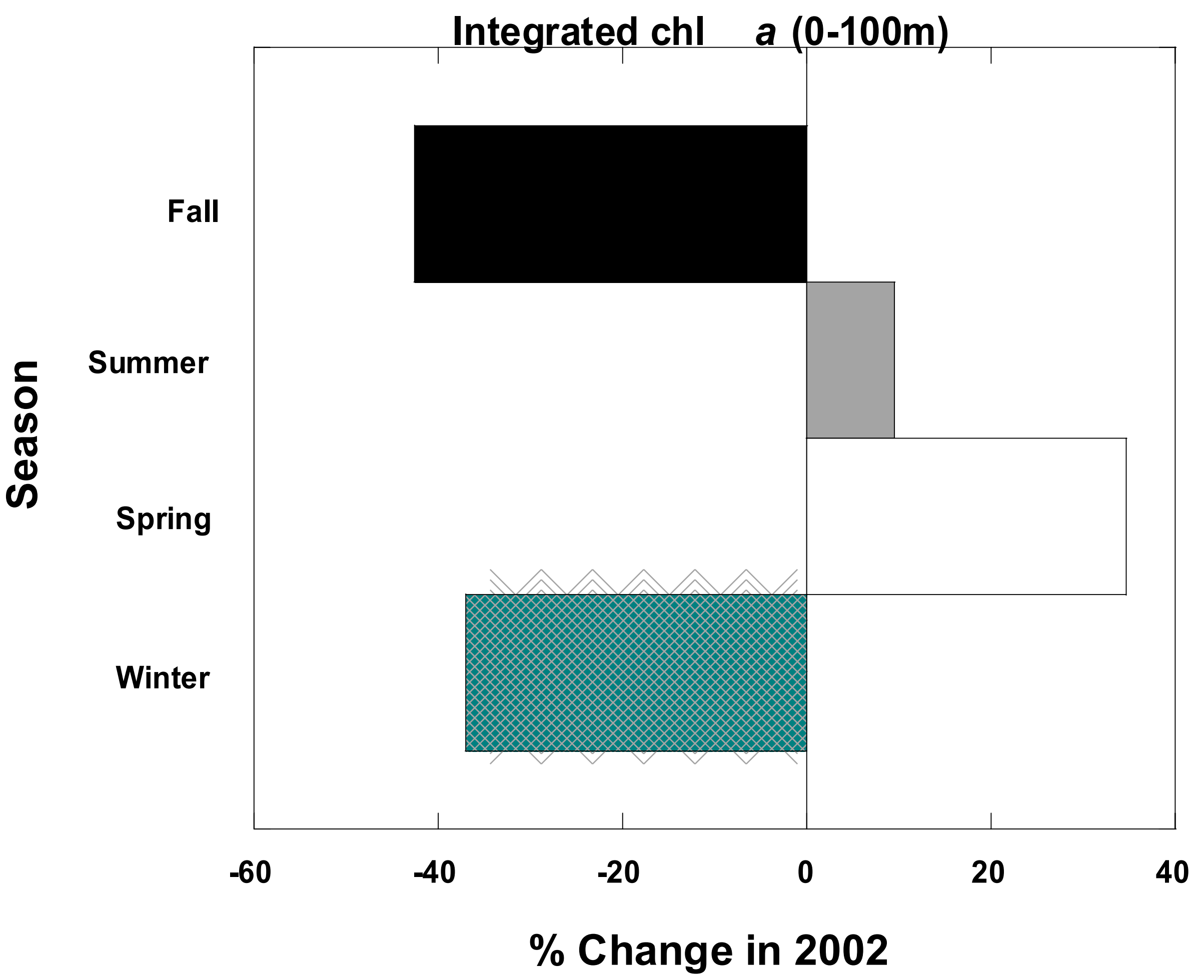

Figure 18. Variation in cell density and relative abundance of major phytoplankton taxa observed at Station 27 from depth-integrated (0-100m) sampling including Diatoms, Dinoflagellates, Flagellates, and major phytoplankton group ratios.

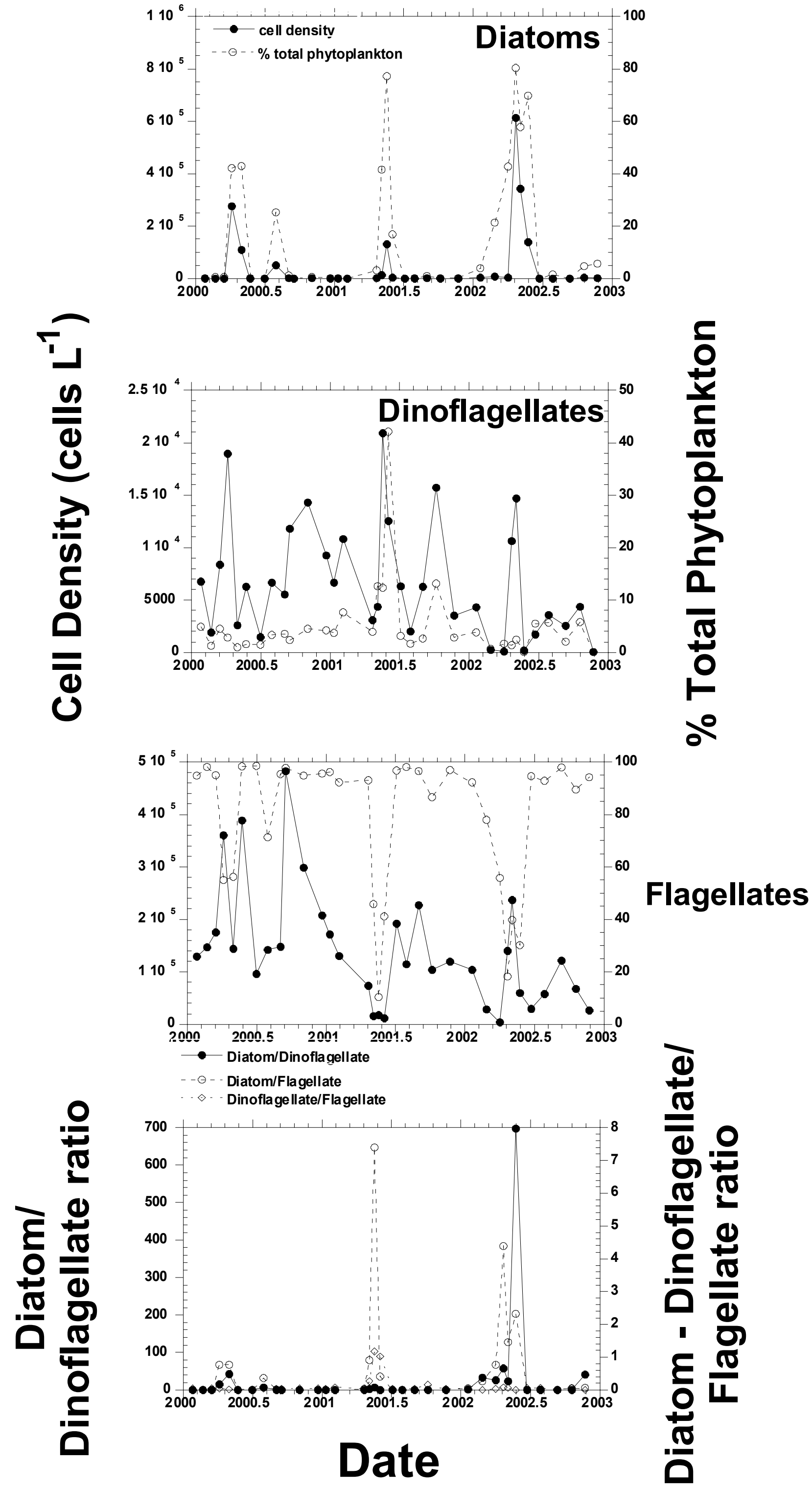

Figure 19. Time series of measured daily primary production (PP) at 10m depth and estimated euphotic-depth integrated primary production (Zeu-PP) at Station 27 during 2000-02. Primary production measures based on P-E (photosynthesis-irradiance) curves derived from laboratory incubations using a photosynthetron.

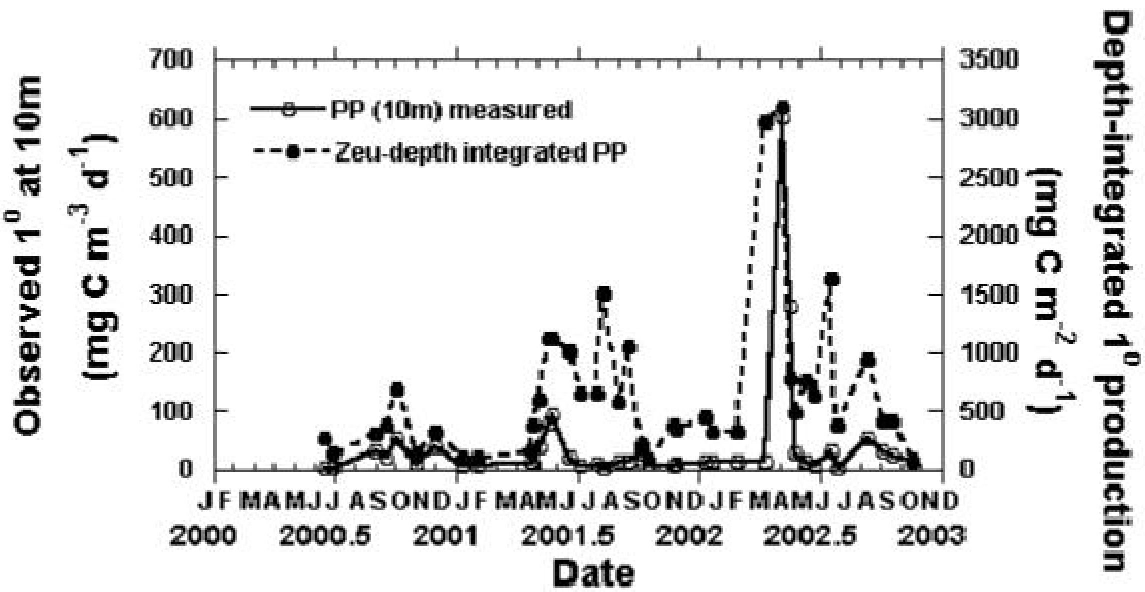

Figure 20. Variability in the vertical attenuation coefficient along section lines during seasonal section occupations in 2002. Sections include Seal Island (SI); Bonavista Bay (BB); Flemish Cap (FC); and Southeast Grand Banks (SEGB). See Figure 1 for detailed station locations.

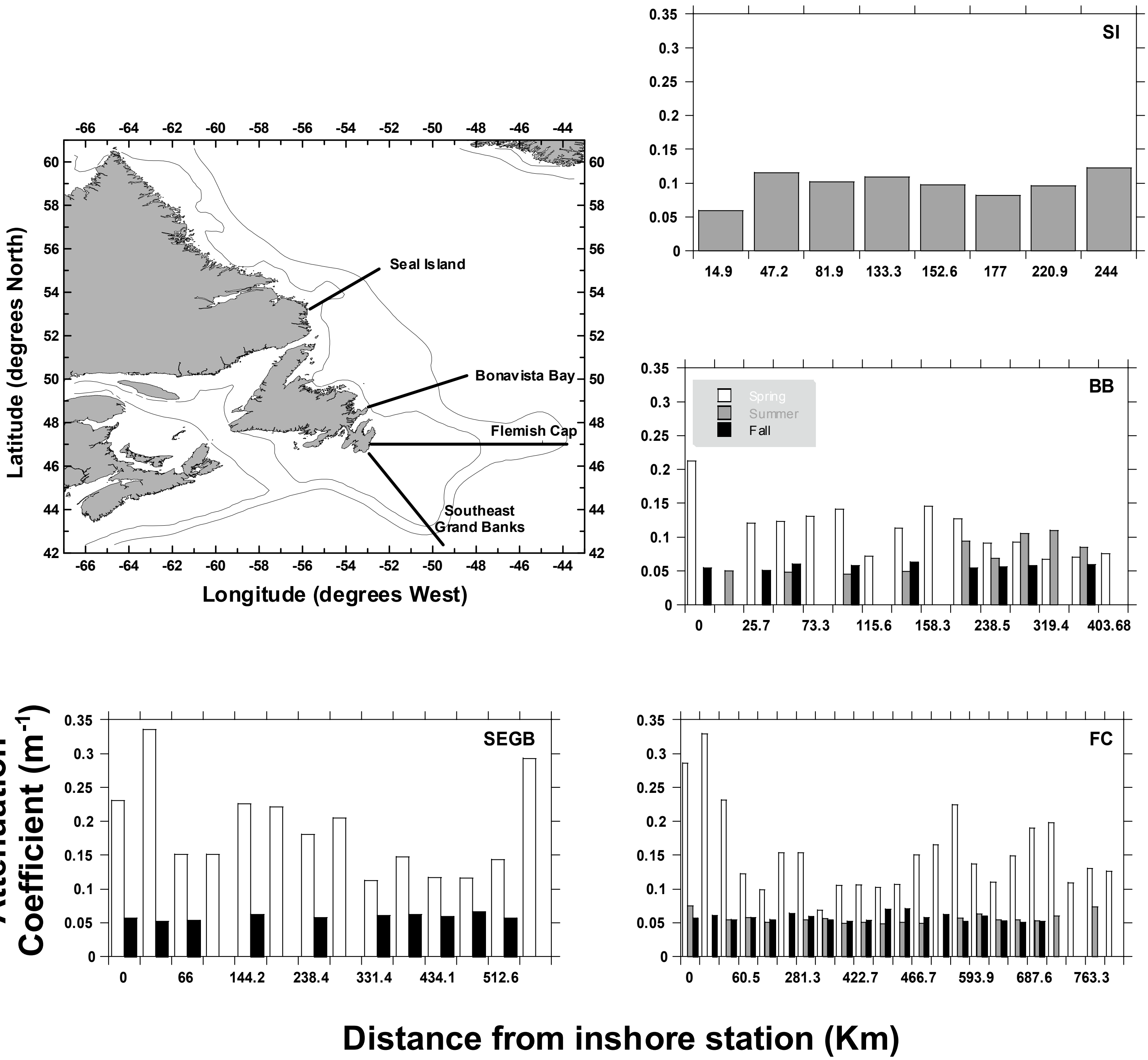

Figure 21. Variability in the euphotic depth (1 % light level) along section lines during seasonal section occupations in 2002. Sections include Seal Island (SI); Bonavista Bay (BB); Flemish Cap (FC); and Southeast Grand Banks (SEGB). See Figure 1 for detailed station locations.

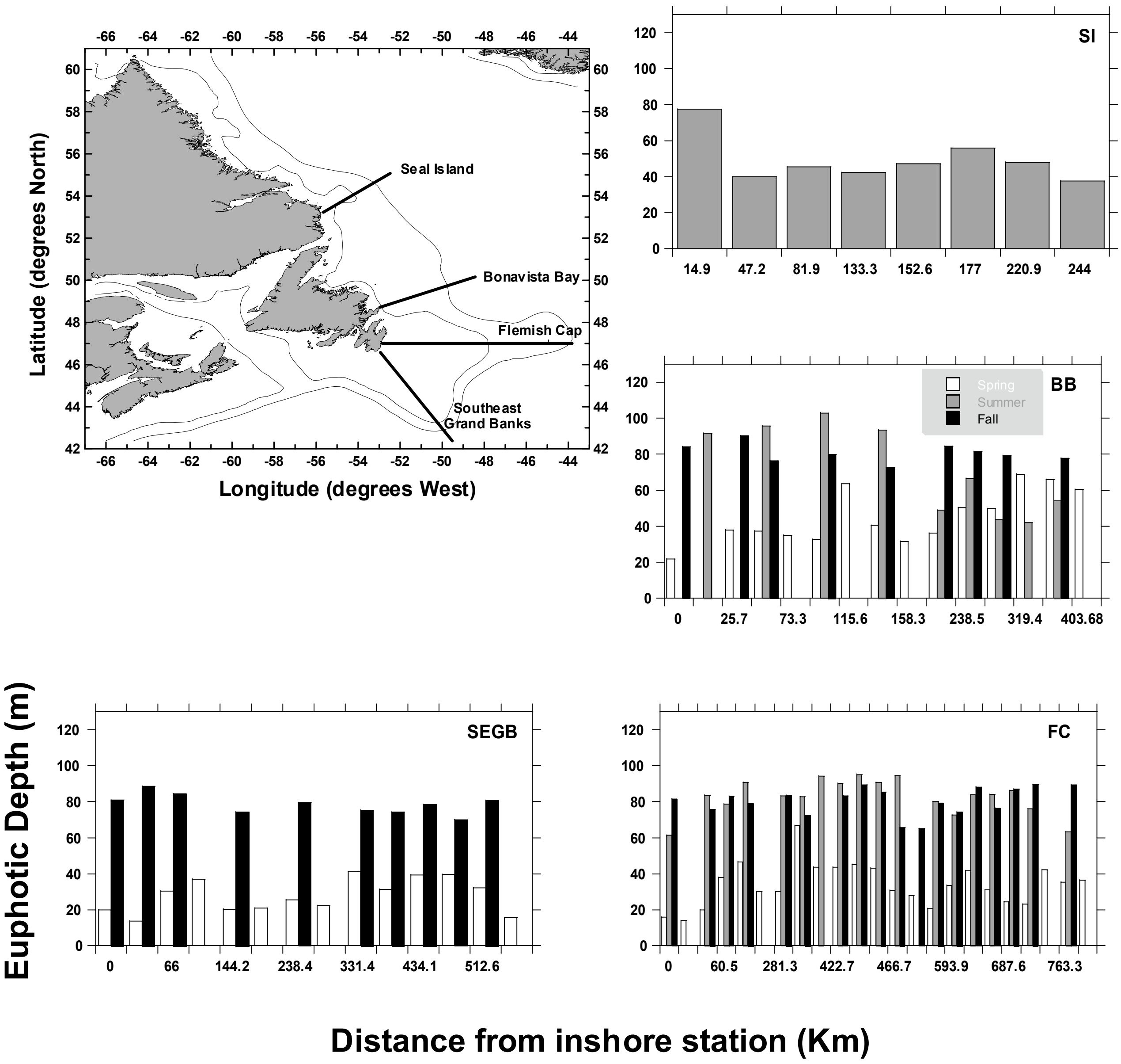

Figure 22. The percent change in vertical attenuation coefficient and euphotic depth (1 % light level) in 2002 compared to earlier years (2000-01) along sections during seasonal occupations. Sections include Seal Island (SI); Bonavista Bay (BB); Flemish Cap (FC); and Southeast Grand Banks (SEGB). See Figure 1 for detailed station locations.

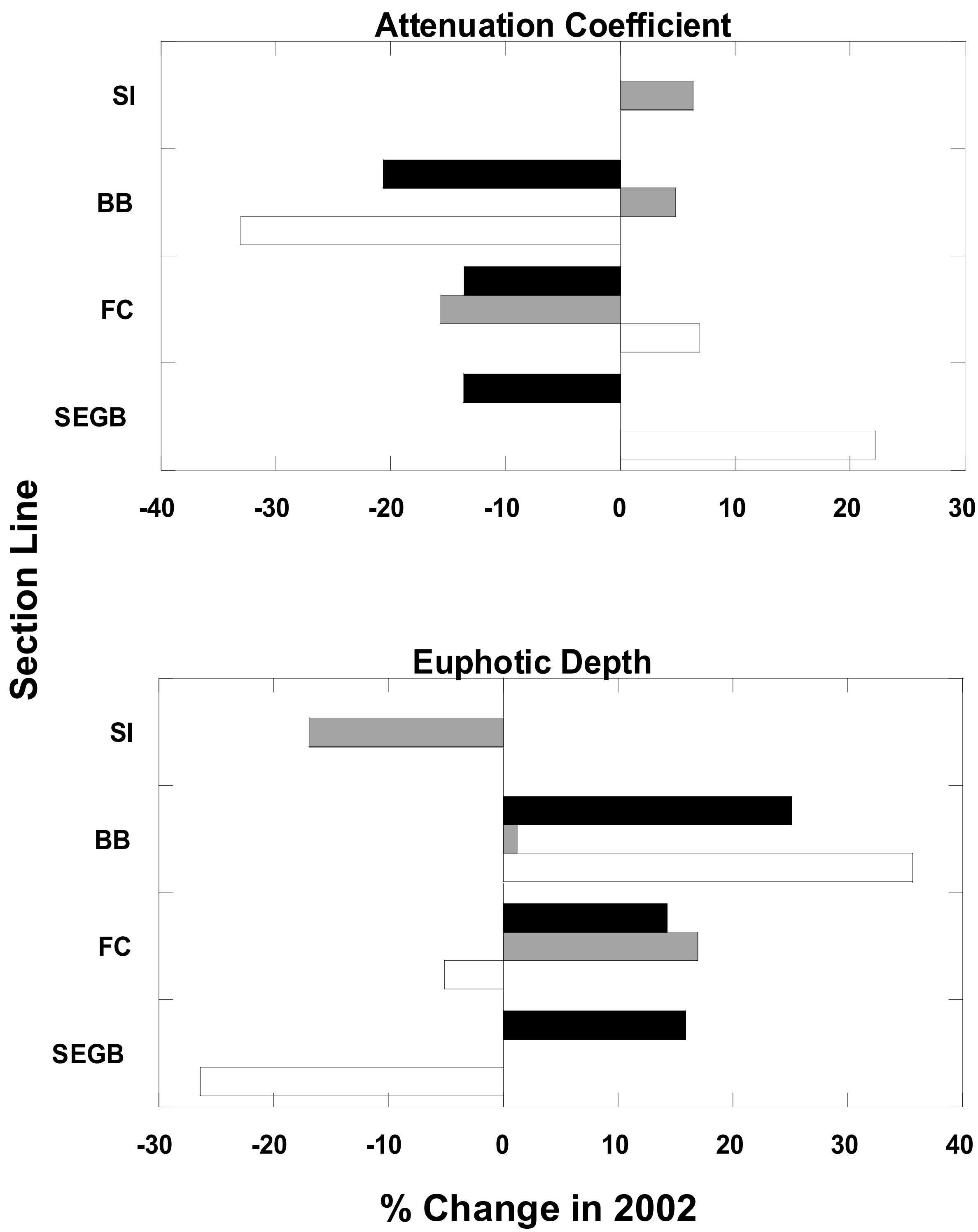

Figure 23. Variability in the stratification index ((Sigma-t 50m – Sigma-t 5m)/45m) along sections during seasonal occupations in 2002. Sections include Seal Island (SI); Bonavista Bay (BB); Flemish Cap (FC); and Southeast Grand Banks (SEGB). See Figure 1 for detailed station locations.

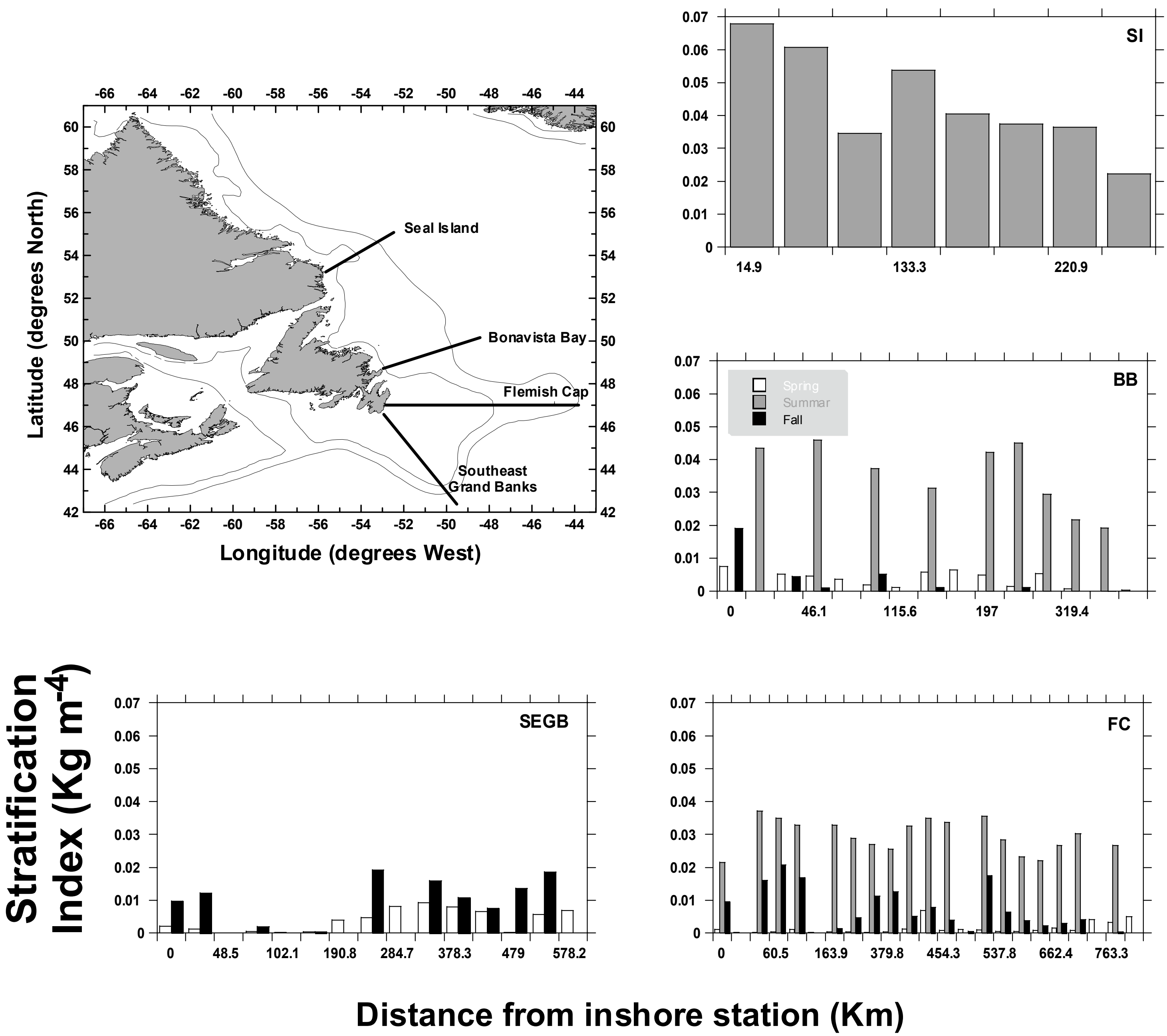

Figure 24. Variability in temperature (0-50m integral) along sections during seasonal occupations in 2002. Sections include Seal Island (SI); Bonavista Bay (BB); Flemish Cap (FC); and Southeast Grand Banks (SEGB). See Figure 1 for detailed station locations.

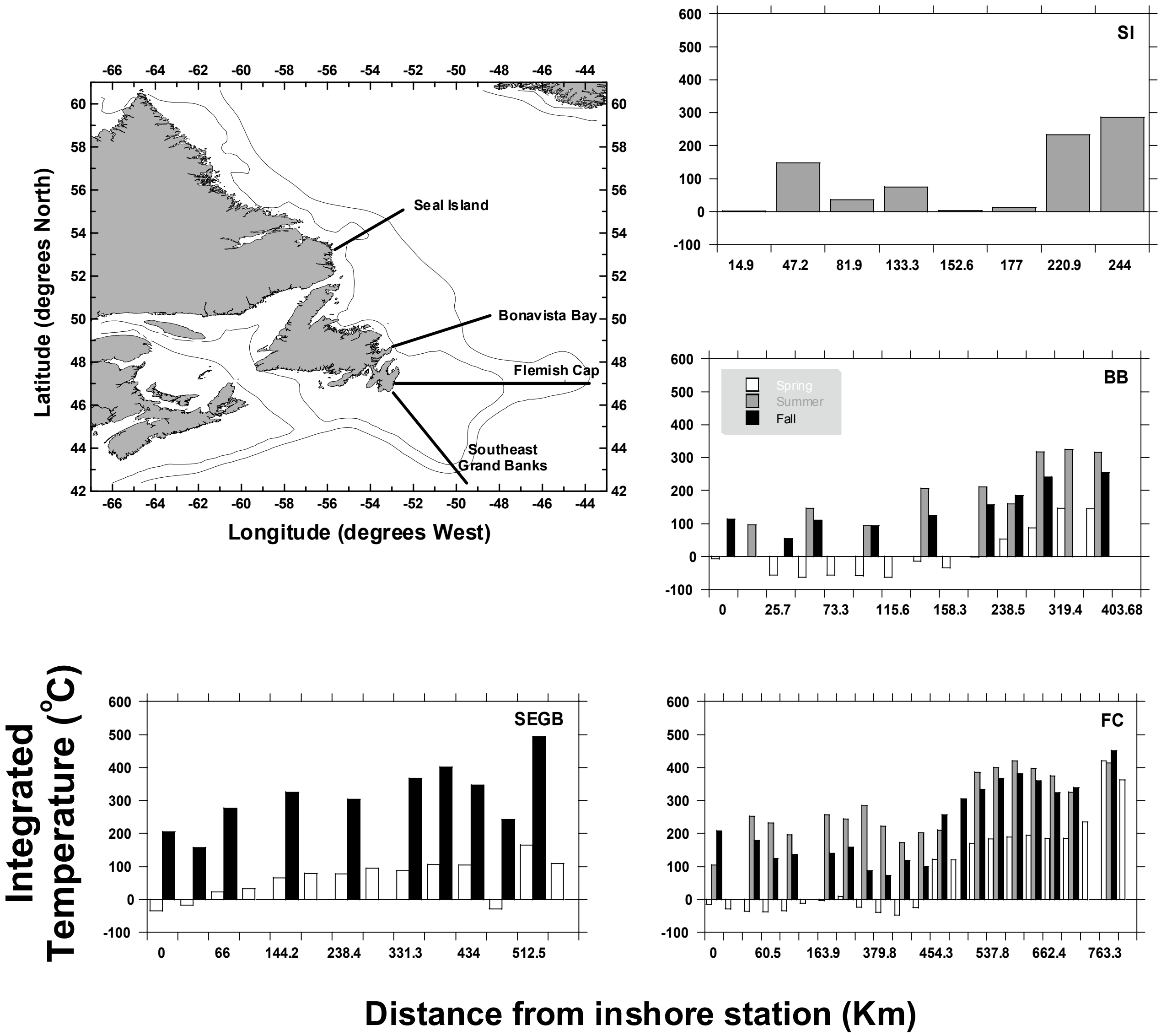

Figure 25. The percent change in the stratification index ((Sigma-t 50 – Sigma-t 5m)/45m) and integrated temperature (0-50m integral) in 2002 compared to earlier years (2000-01) along sections during seasonal occupations. Sections include Seal Island (SI); Bonavista Bay (BB); Flemish Cap (FC); and Southeast Grand Banks (SEGB). See Figure 1 for detailed station locations.

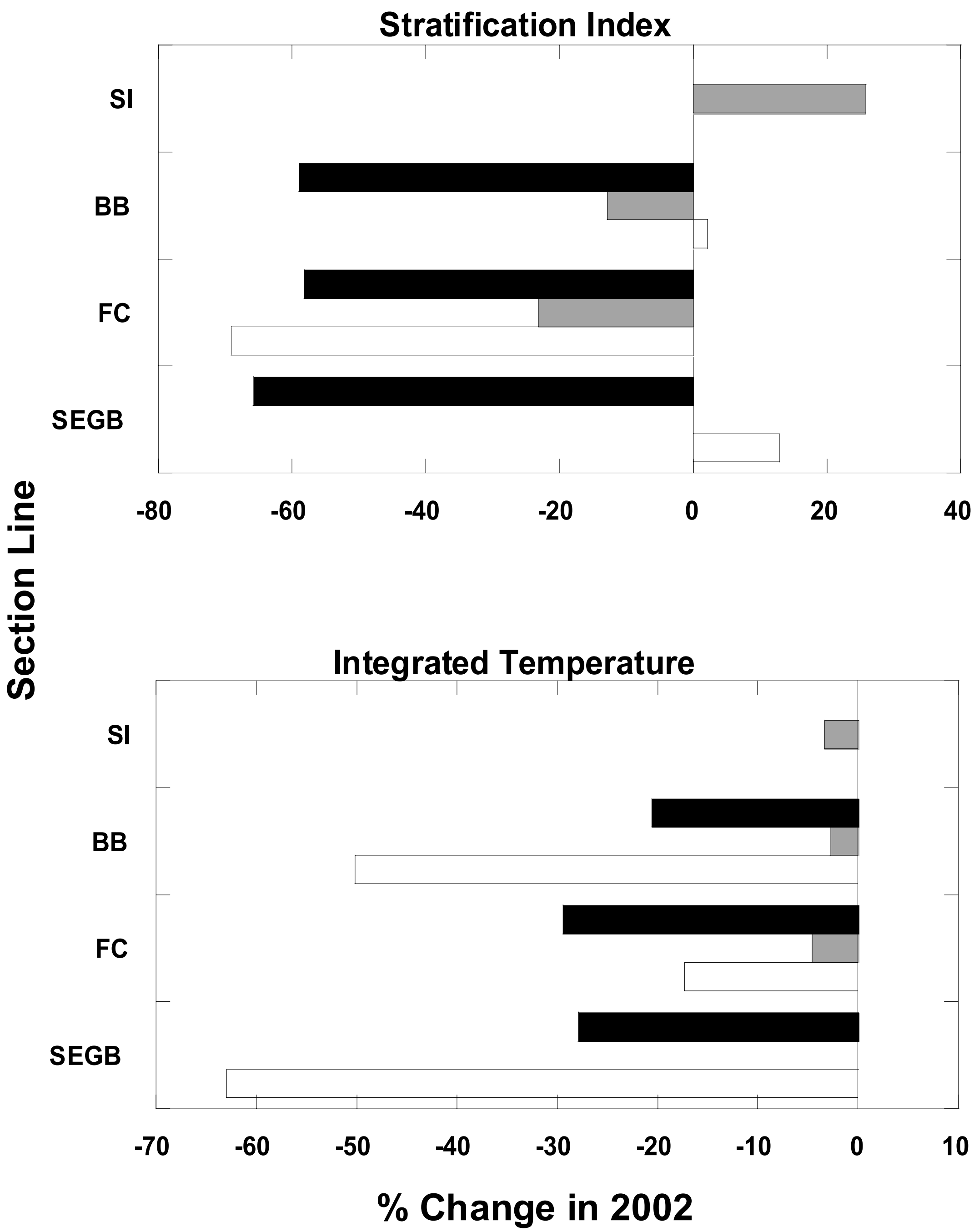

Figure 26. The Spring 2002 concentrations (mmol m^{-3}) of silicate, nitrate, and chlorophyll a (mg m^{-3})versus depth along AZMP sections including Bonavista Bay (BB); Flemish Cap (FC); and Southeast Grand Banks (SEGB). See Figure 1 for sample locations.

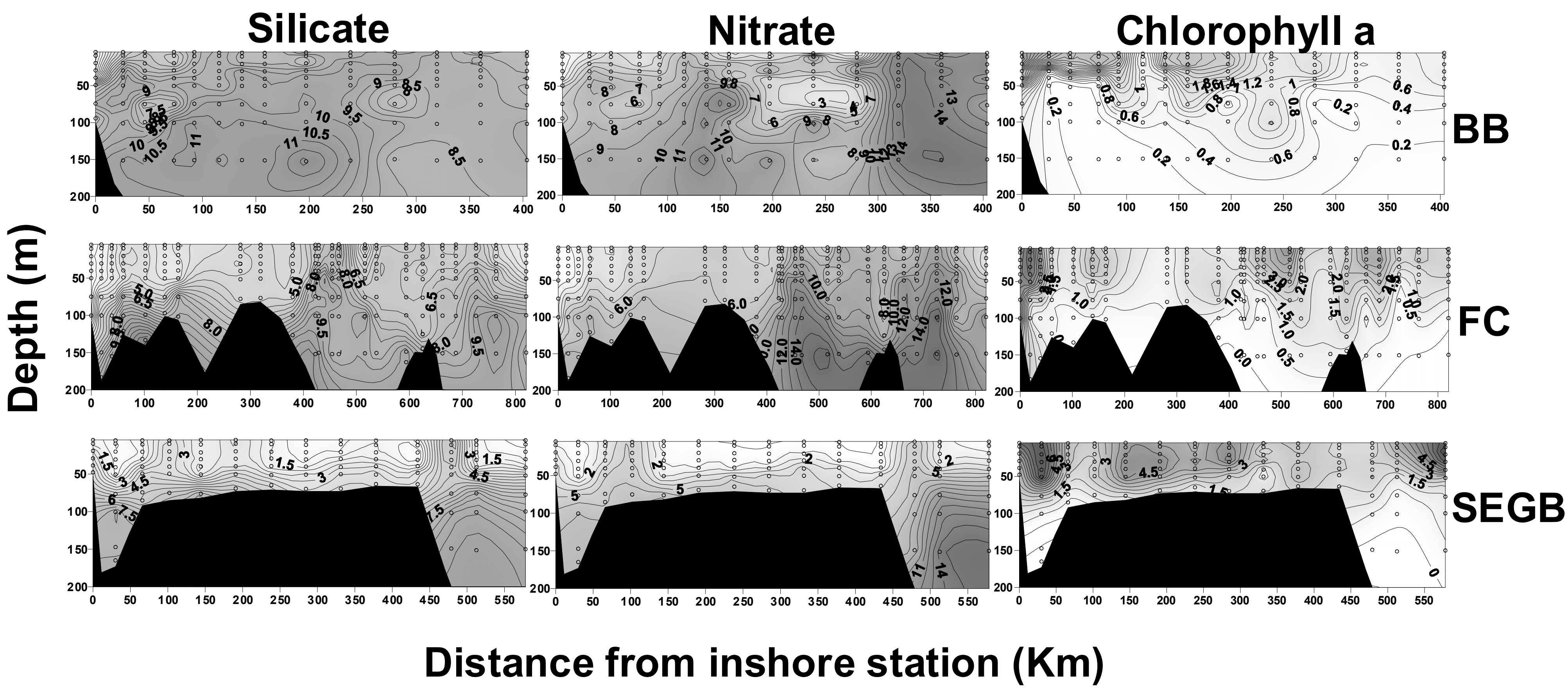

Figure 27. The Summer 2002 concentrations (mmol m^{-3}) of silicate, nitrate, and chlorophyll a (mg m^{-3}) versus depth along AZMP sections including Bonavista Bay (BB); Flemish Cap (FC); and Seal Island (SI). See Figure 1 for sample locations.

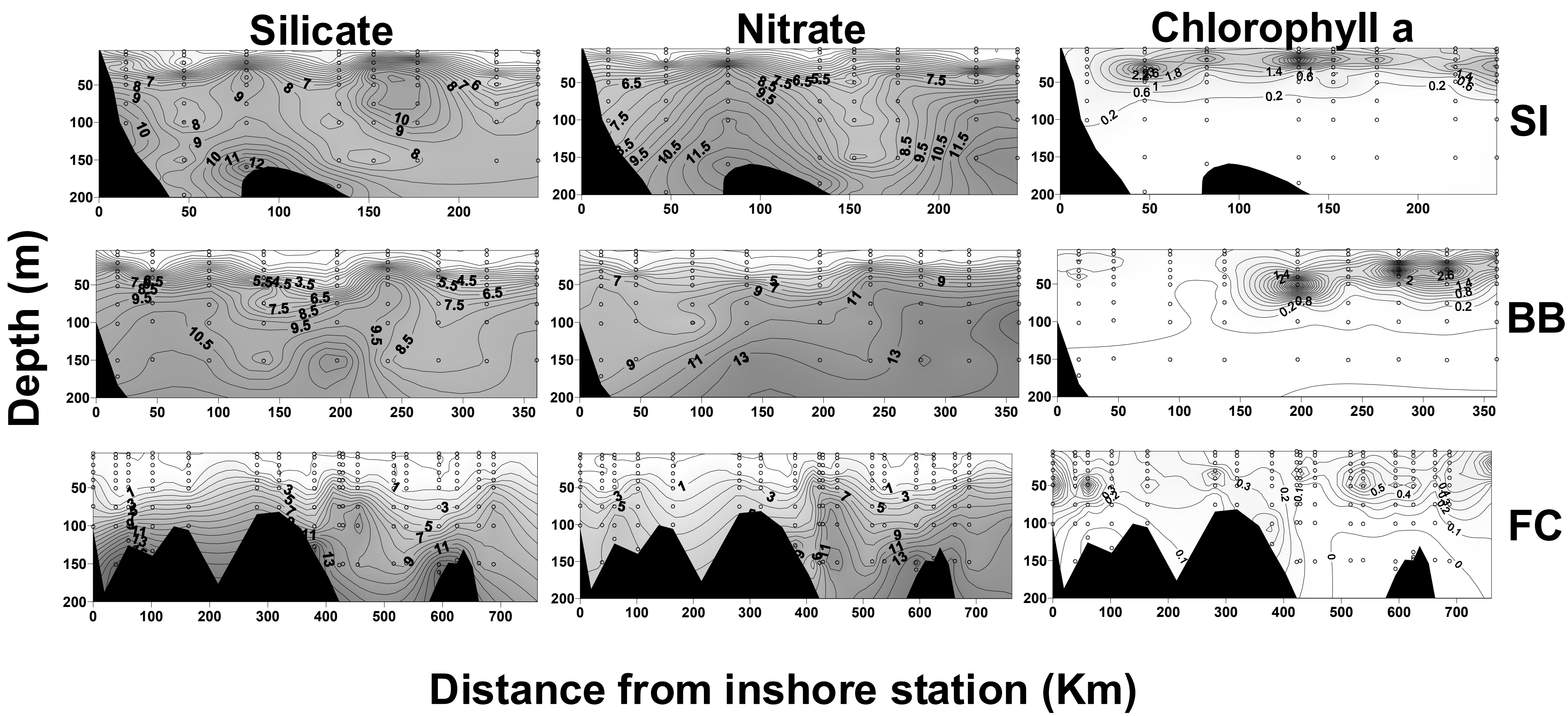

Figure 28. The Fall 2002 concentrations (mmol m^{-3}) of silicate, nitrate, and chlorophyll a (mg m^{-3}) versus depth along AZMP sections including Bonavista Bay (BB); Flemish Cap (FC); and Southeast Grand Banks (SEGB). See Figure 1 for sample locations.

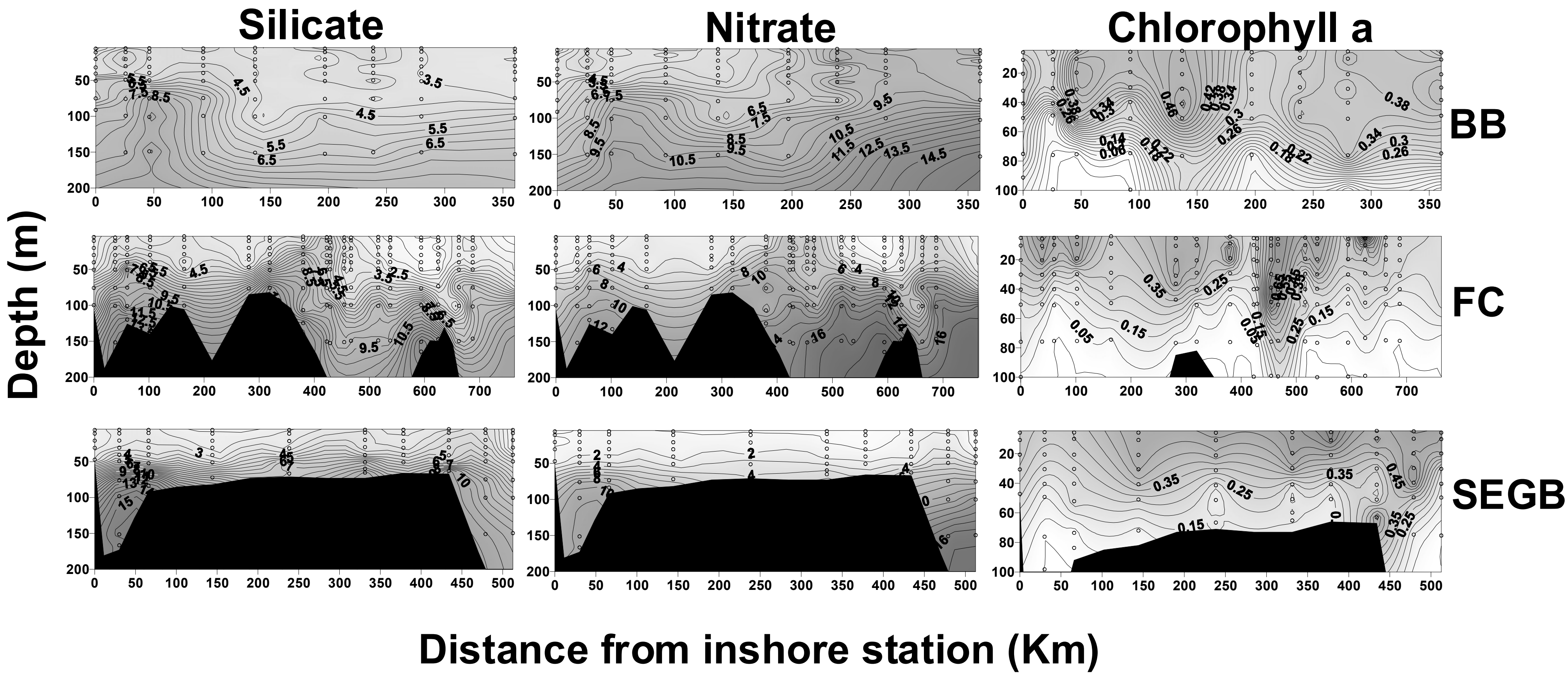

Figure 29. Variability in silicate inventories (0-50m integral) along sections during seasonal occupations in 2002. Sections include Seal Island (SI); Bonavista Bay (BB); Flemish Cap (FC); and Southeast Grand Banks (SEGB). See Figure 1 for detailed station locations.

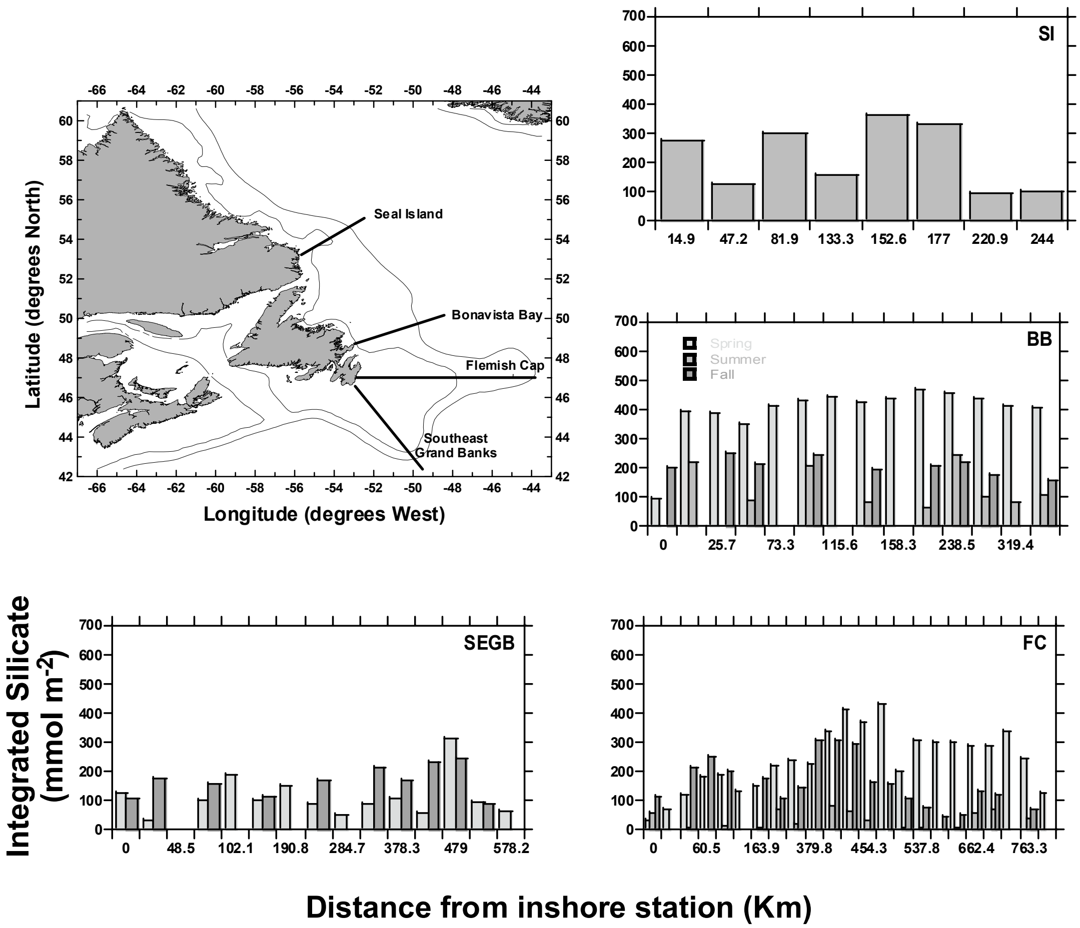

Figure 30. Variability in nitrate inventories (0-50m integral) along sections during seasonal occupations in 2002. Sections include Seal Island (SI); Bonavista Bay (BB); Flemish Cap (FC); and Southeast Grand Banks (SEGB). See Figure 1 for detailed station locations.

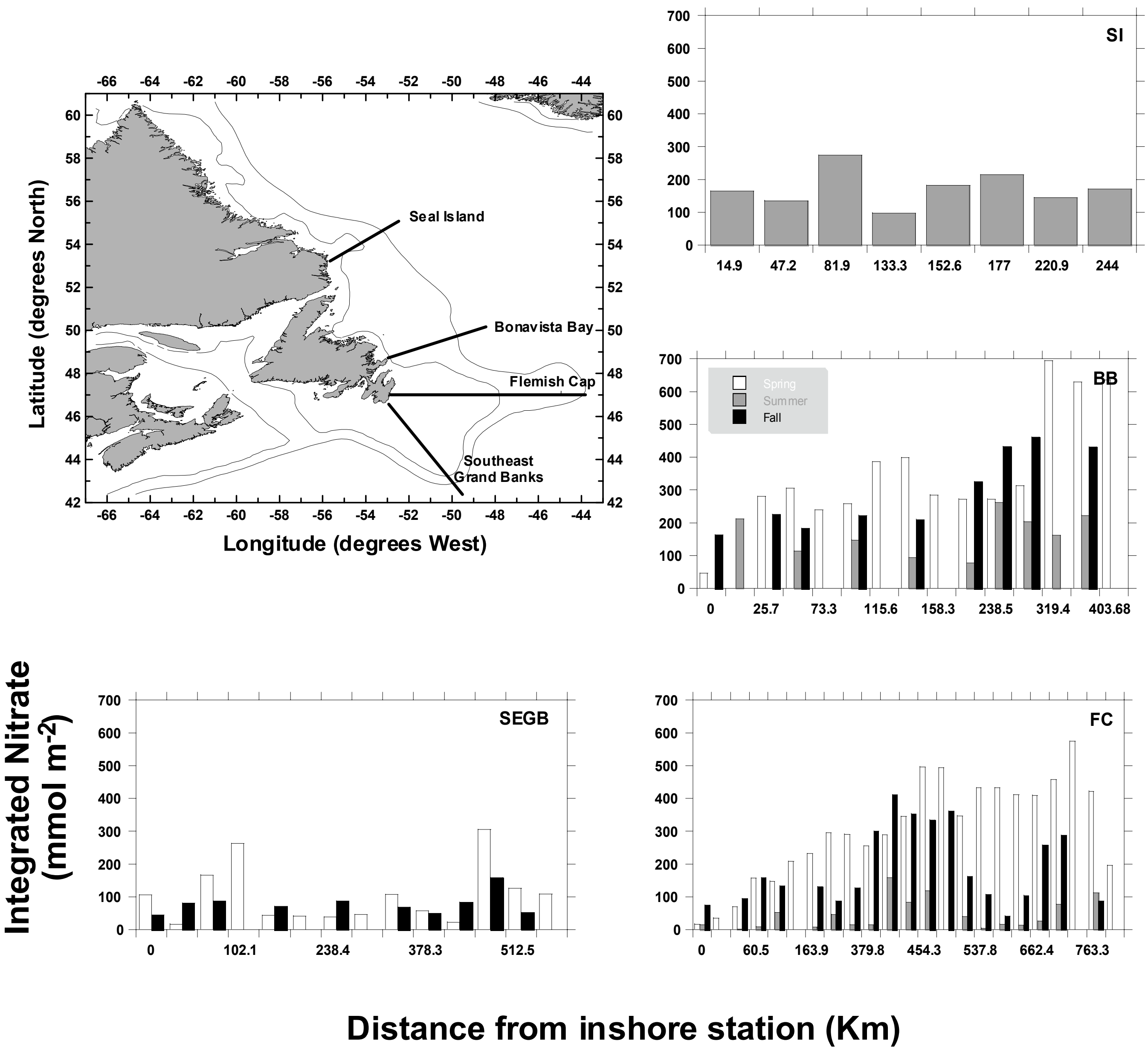

Figure 31. Variability in silicate inventories (50-150m integral) along sectios during seasonal occupations in 2002. Sections include Seal Island (SI); Bonavista Bay (BB); Flemish Cap (FC); and Southeast Grand Banks (SEGB). See Figure 1 for detailed station locations.

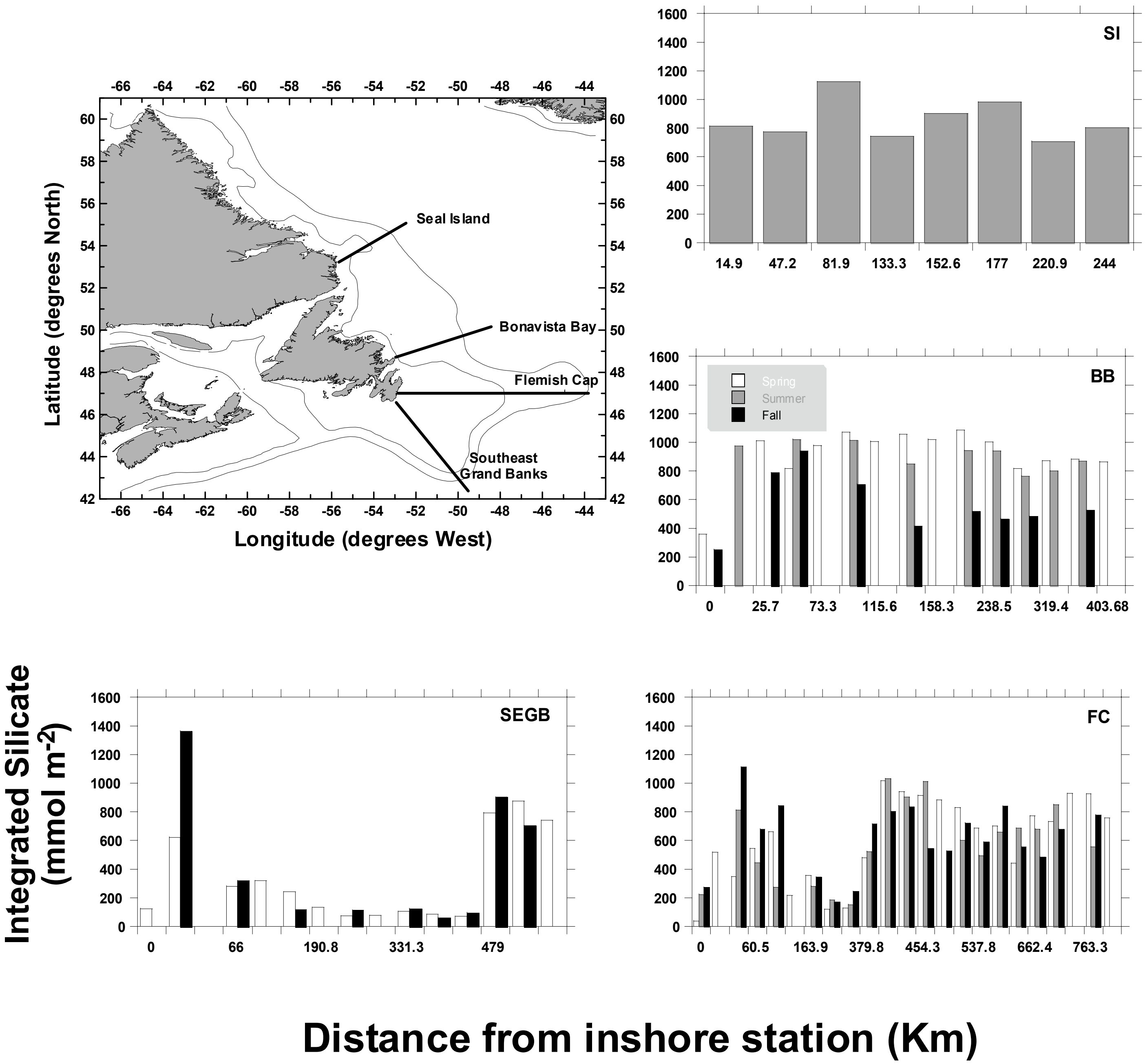

Figure 32. Variability in deep nitrate inventories (50-150m integral) along sections during seasonal occupations in 2002. Sections include Seal Island (SI); Bonavista Bay (BB); Flemish Cap (FC); and Southeast Grand Banks (SEGB). See Figure 1 for detailed station locations.

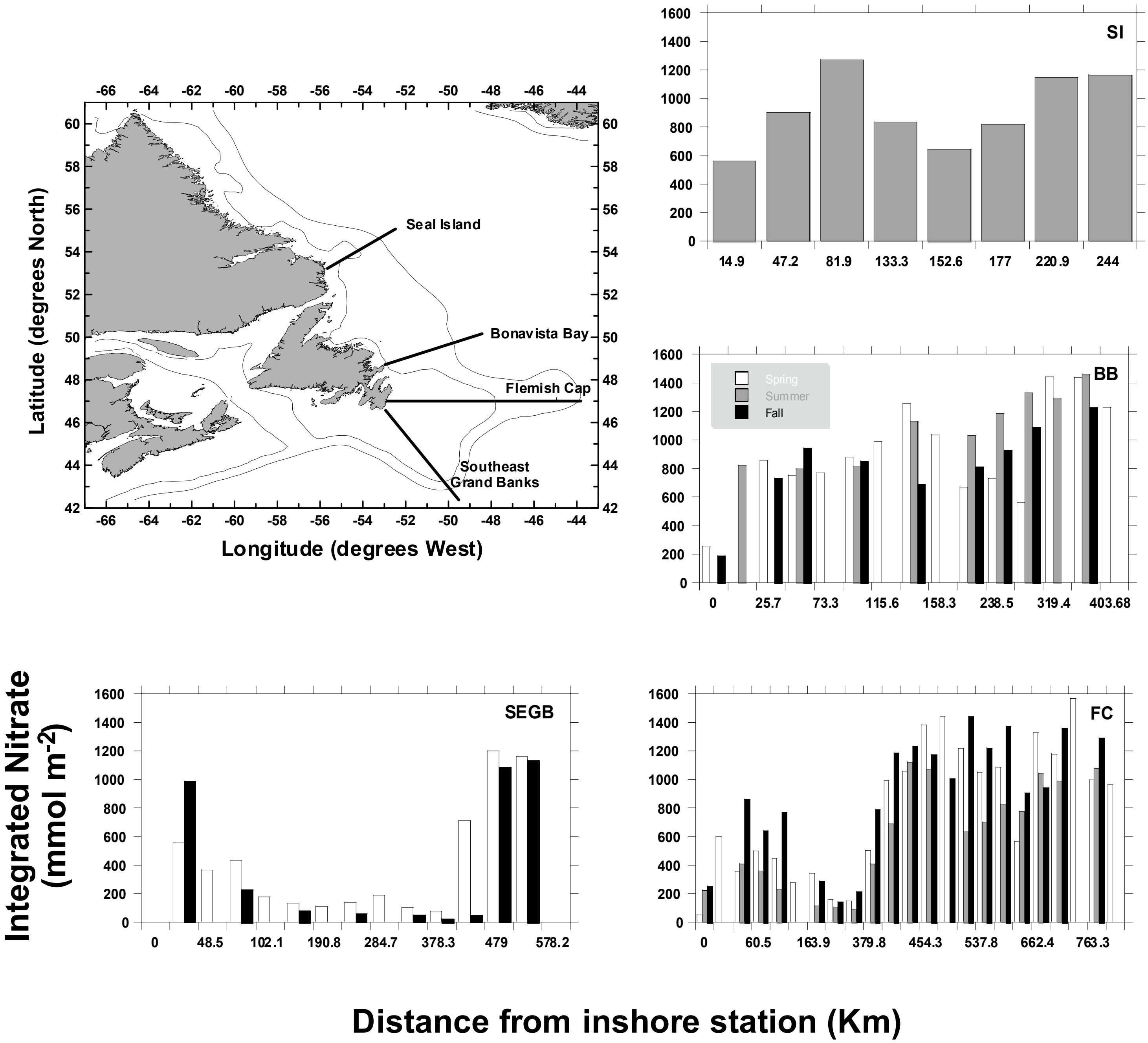

Figure 33. The percent change in major nutrient inventories in 2002 compared to earlier years (2000-01) along sections during seasonal occupations. Sections include Seal Island (SI); Bonavista Bay (BB); Flemish Cap (FC); and Southeast Grand Banks (SEGB). See Figure 1 for detailed station locations.

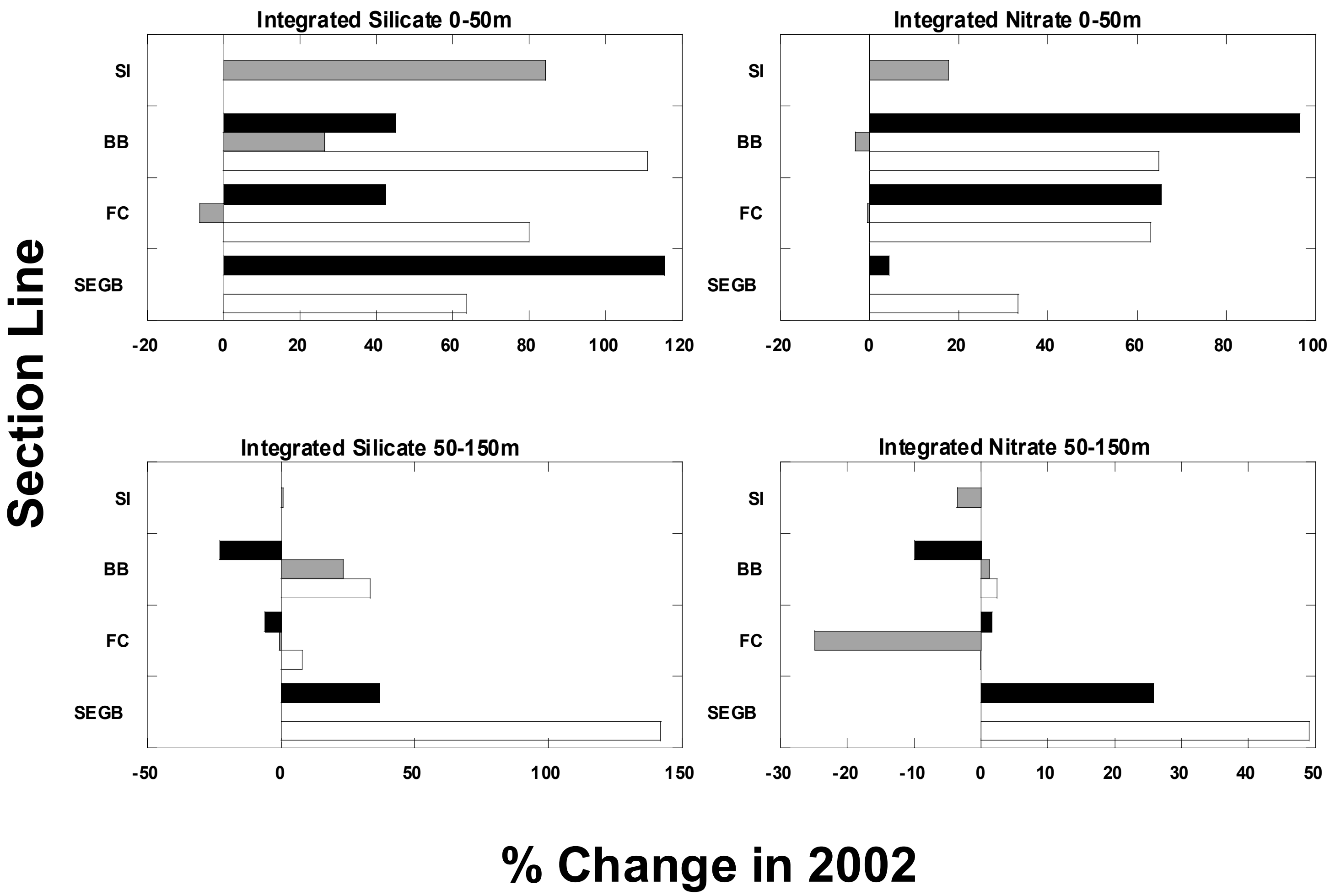

Figure 34. Variability in chlorophyll *a* inventories (0-100m integral) along sections during seasonal occupations in 2002. Sections include Seal Island (SI); Bonavista Bay (BB); Flemish Cap (FC); and Southeast Grand Banks (SEGB). See Figure 1 for detailed station locations.

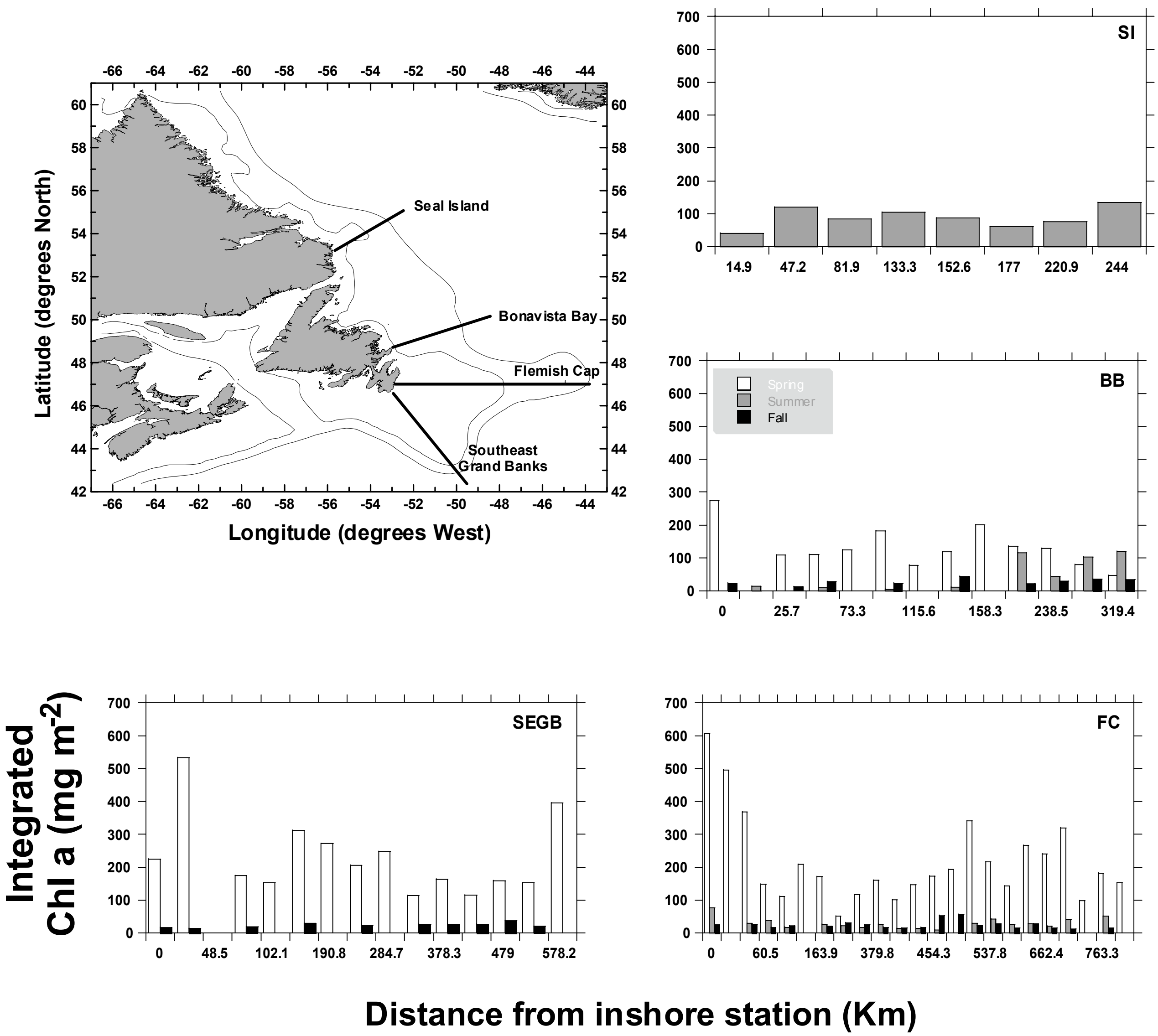

Figure 35. The percent change in chlorophyll a inventory (0-100m integral) in 2002 compared to earlier years (2000-01) along sections during seasonal occupations. Sections include Seal Island (SI); Bonavista Bay (BB); Flemish Cap (FC); and Southeast Grand Banks (SEGB). See Figure 1 for detailed station locations.

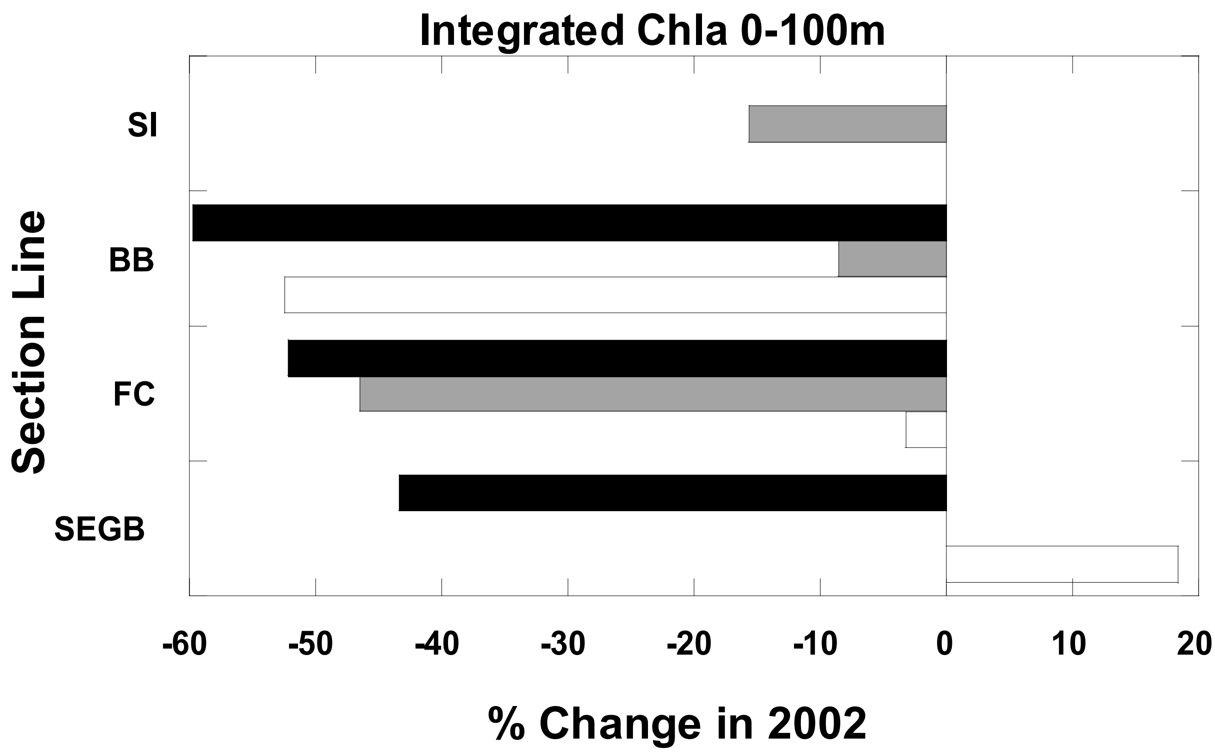

Figure 36. Variation in abundance of major phytoplankton taxa at selected stations along the standard oceanographic sections in spring 2002.

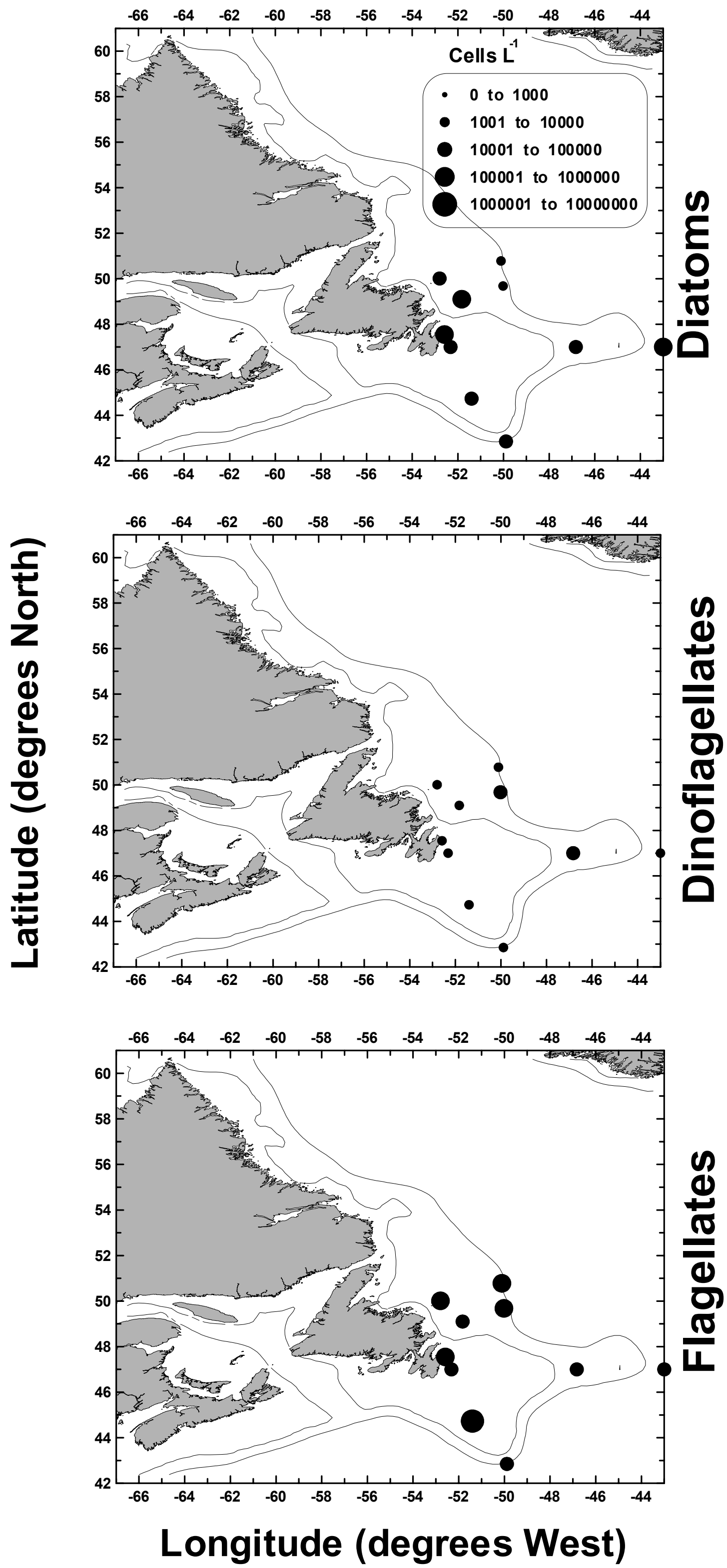

Figure 37. Variation in abundance of major phytoplankton taxa at selected stations along the standard oceanographic sections in summer 2002. Identical legend as in Figure 36.

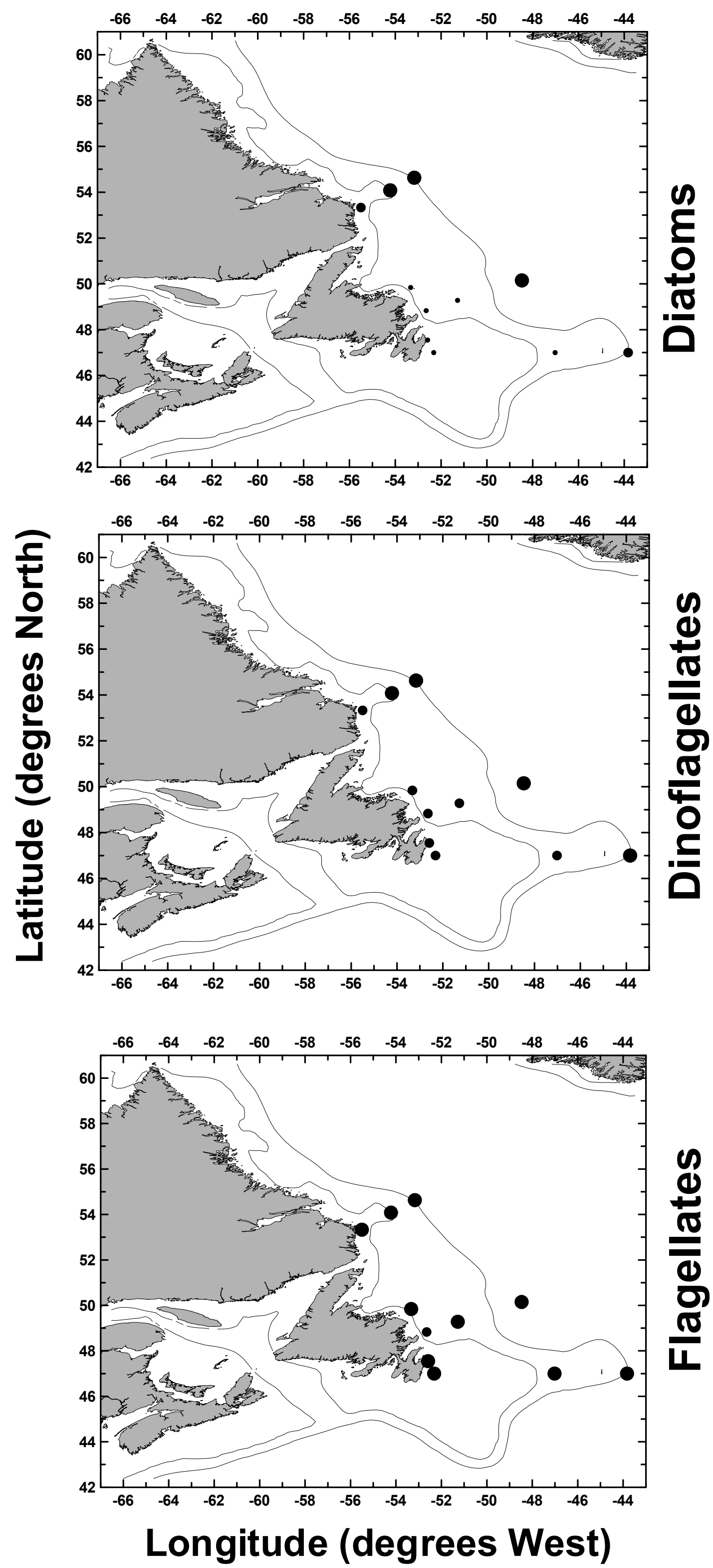

Figure 38. Variation in abundance of major phytoplankton taxa at selected stations along the standard oceanographic sections in fall 2002. Identical legend as in Figure 36.

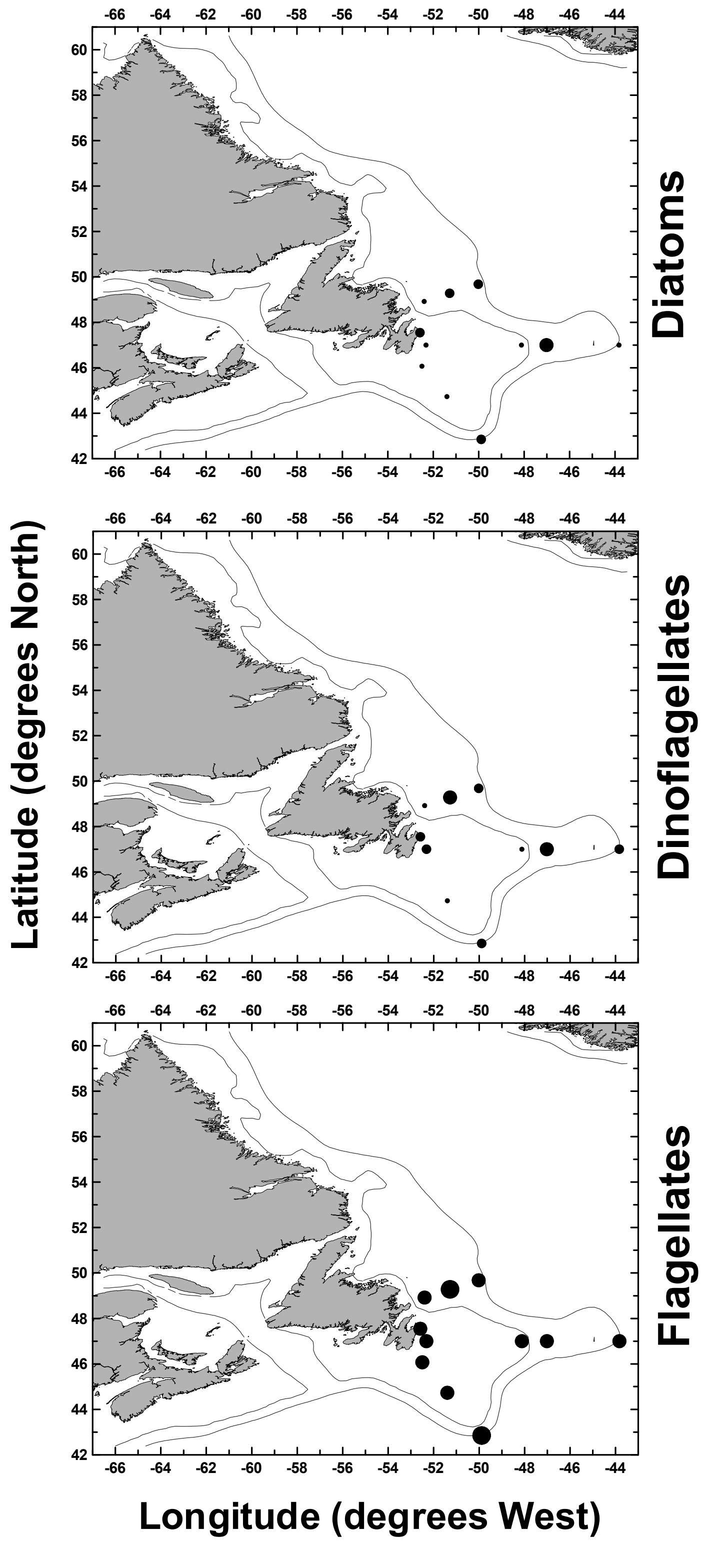

Figure 39. Time series of surface (upper 20m) chlorophyll a concentrations obtained from SeaWiFS bi-weekly ocean colour composites for selected sub-regions along the Newfoundland and Labrador Shelf during 1998-2002 (Sep. 1997-Aug. 2002).

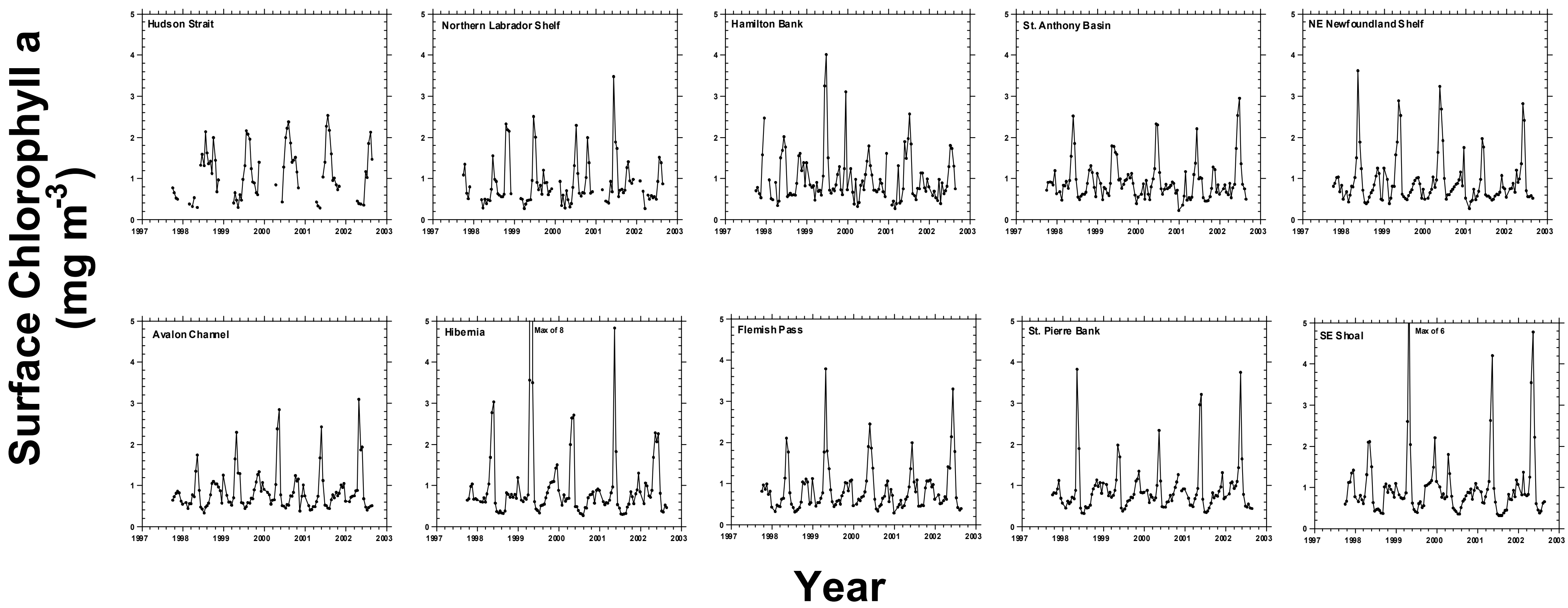

Figure 40. Variability in annual mean surface (ca. upper 20m) chlorophyll a concentrations (from SeaWiFS bi-weekly ocean colour composites) and timing of the spring bloom for selected statistical sub-regions in the NW Atlantic (see Harrison et al. 2002 for overview of all regions) for the years 1998-2002.

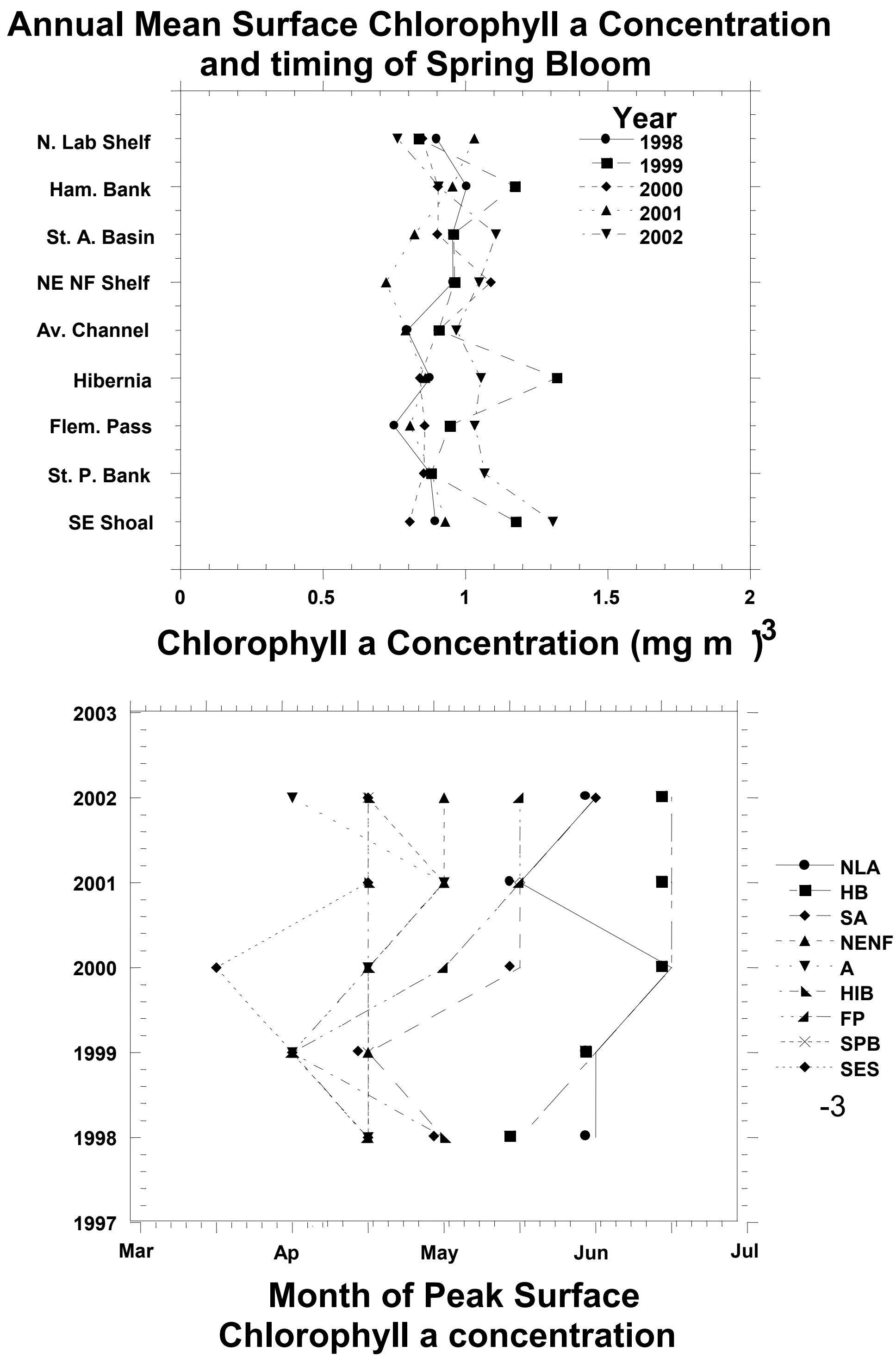

Figure 41. Time series of total zooplankton abundance (upper panel) and relative species composition (Lower panel) from vertical net collections performed at Station 27 since the inception of the AZMP.

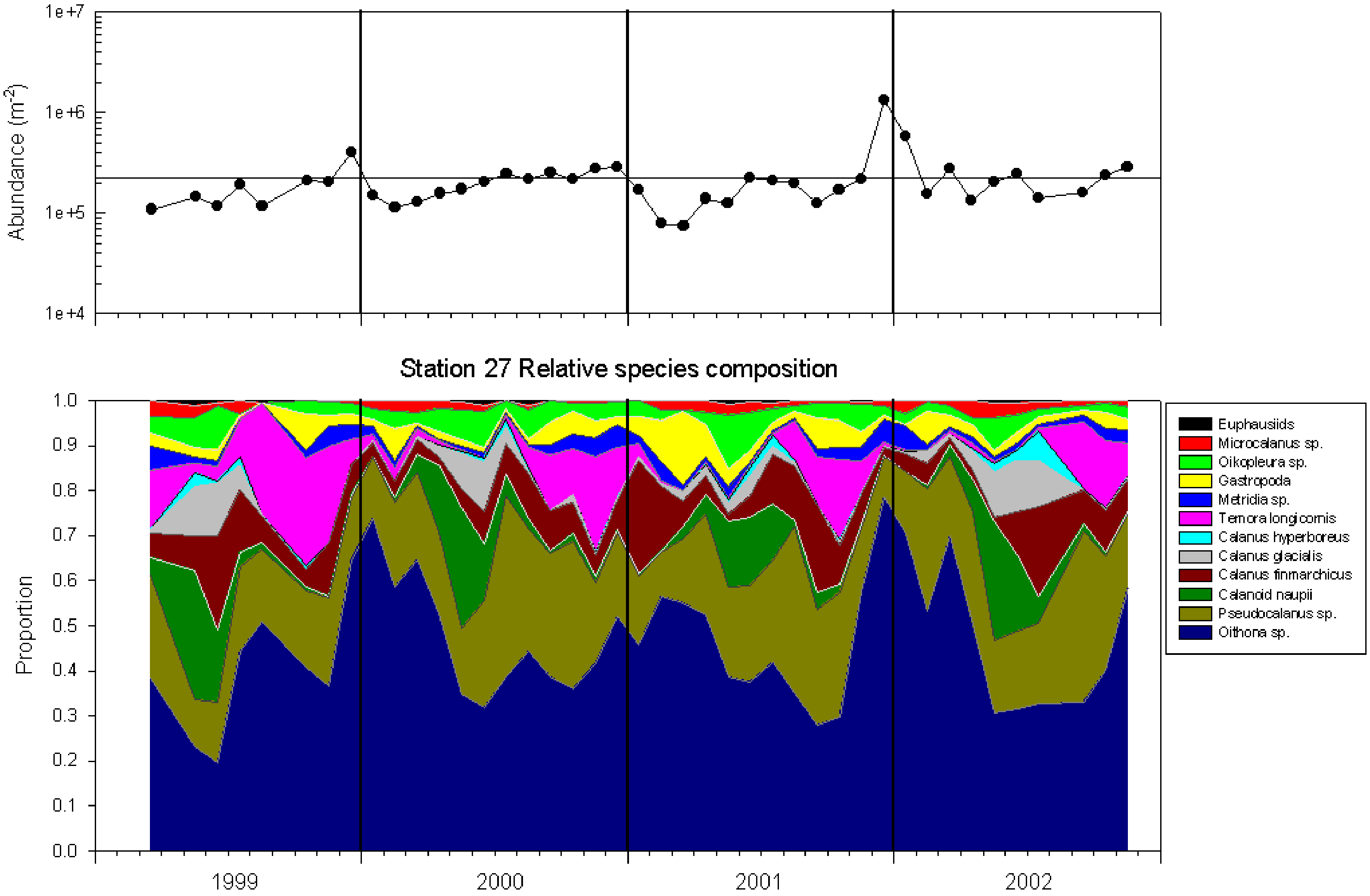

Figure 42. Time series of abundance (m-2) for selected zooplankton taxa from Station 27 since the inception of AZMP. The solid horizontal line represents the overall mean abundance (which includes zero values) from the time series for each taxa and serves only as a reference point.

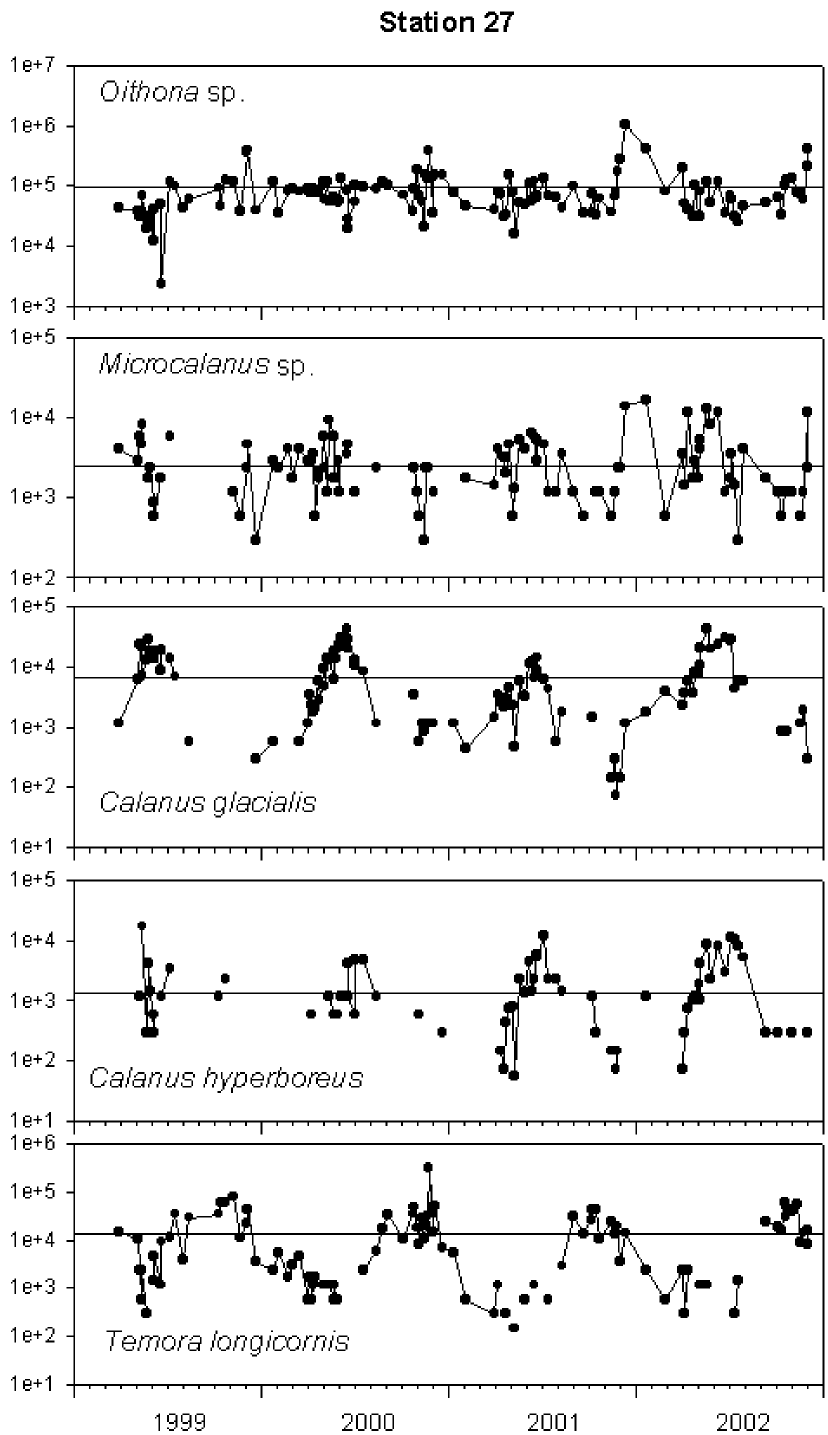

Figure 42 continued.

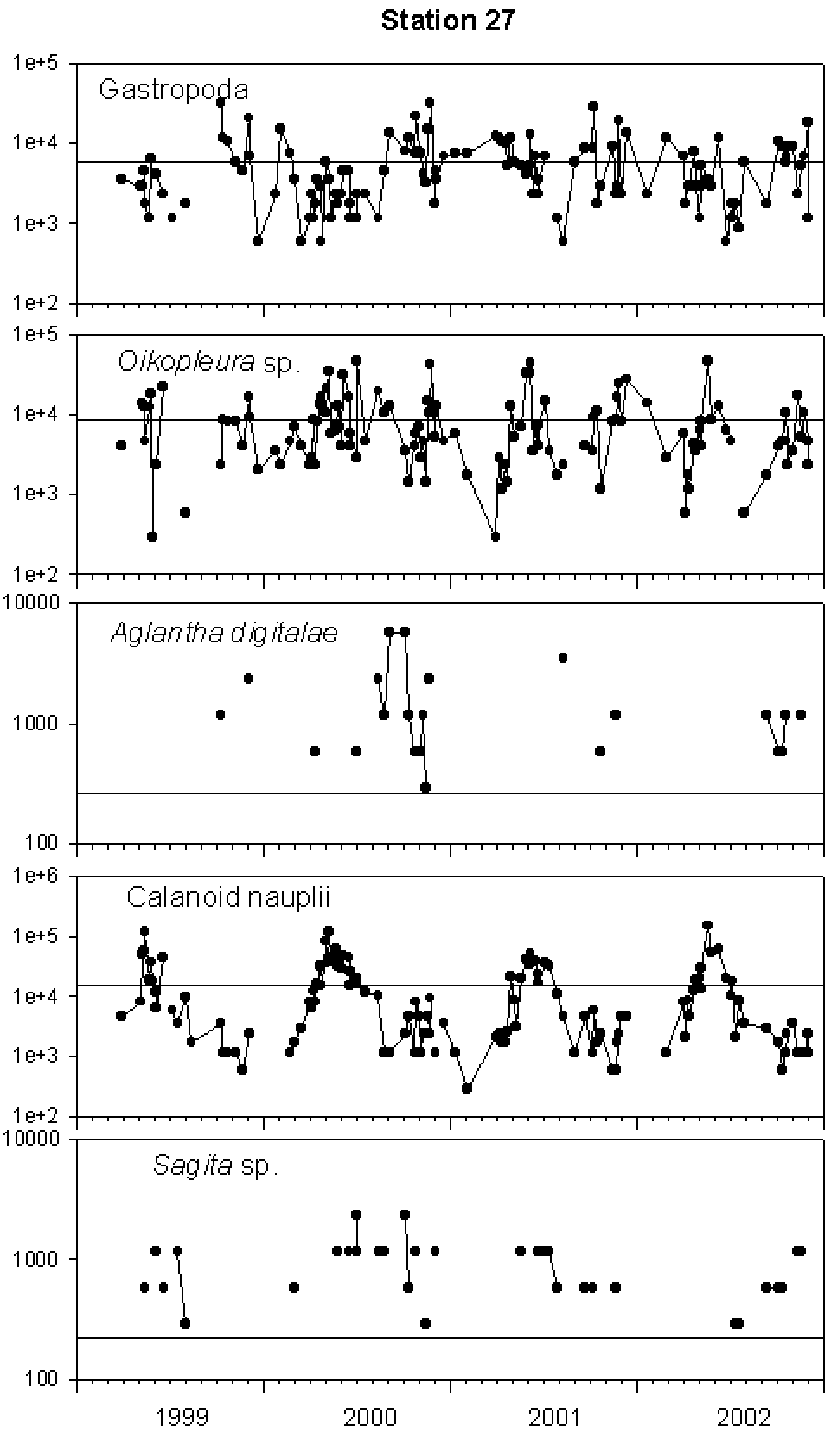

Figure 43. Time series of abundance and copepodite relative stage composition of *Calanus finmarchicus* at Station 27. The tick marks at the top of the figure indicates the collection times of samples.

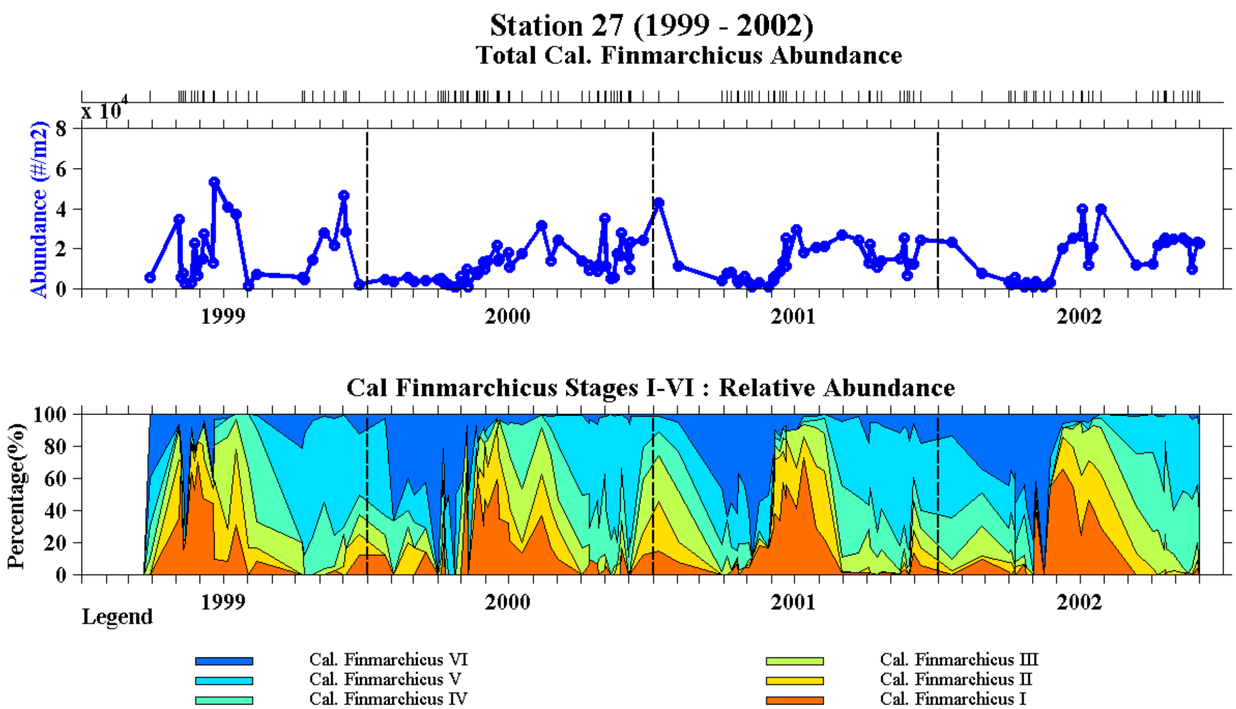

Figure 44. Time series of abundance and copepodite relative stage composition of *Pseudocalanus* sp. at Station 27. The tick marks at the top of the figure indicates the collection times of samples.

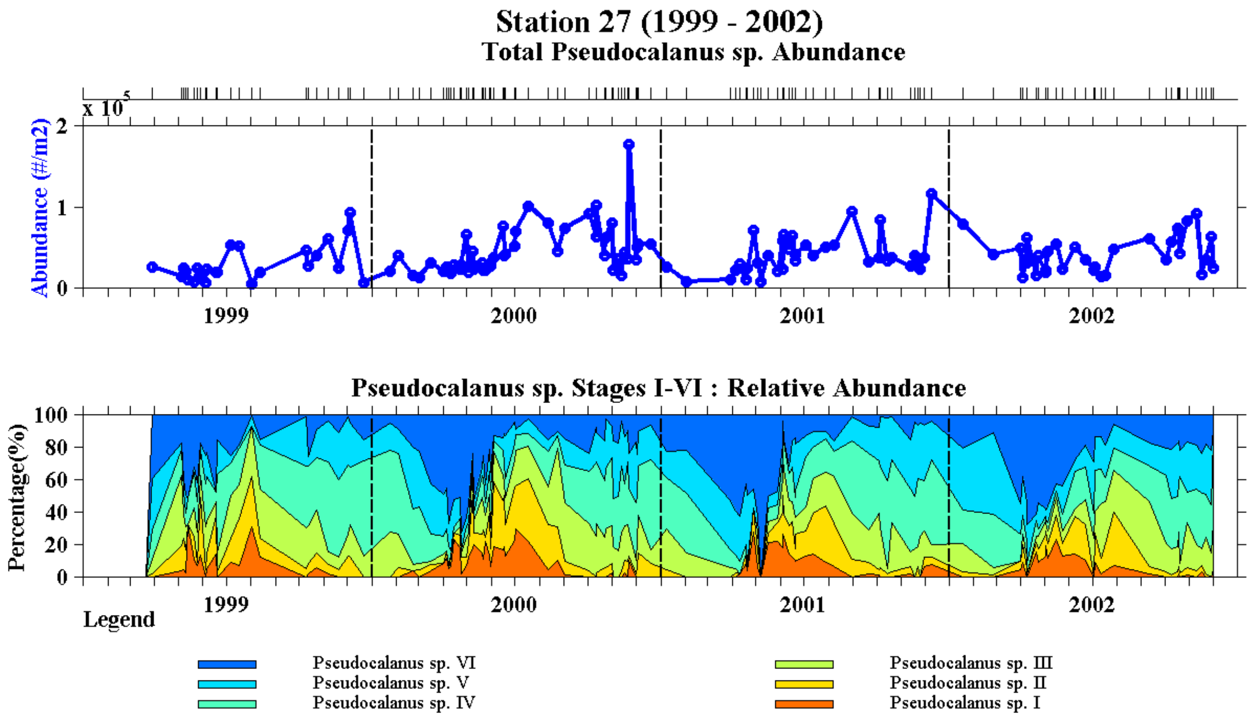

Figure 45. Total zooplankton abundance during fall surveys of the Newfoundland Shelf for the period 1999-2001. Station locations are indicated on the corresponding map. Missing bars indicate that a station was not sampled in a given year and do not indicate the absence of zooplankton at that site.

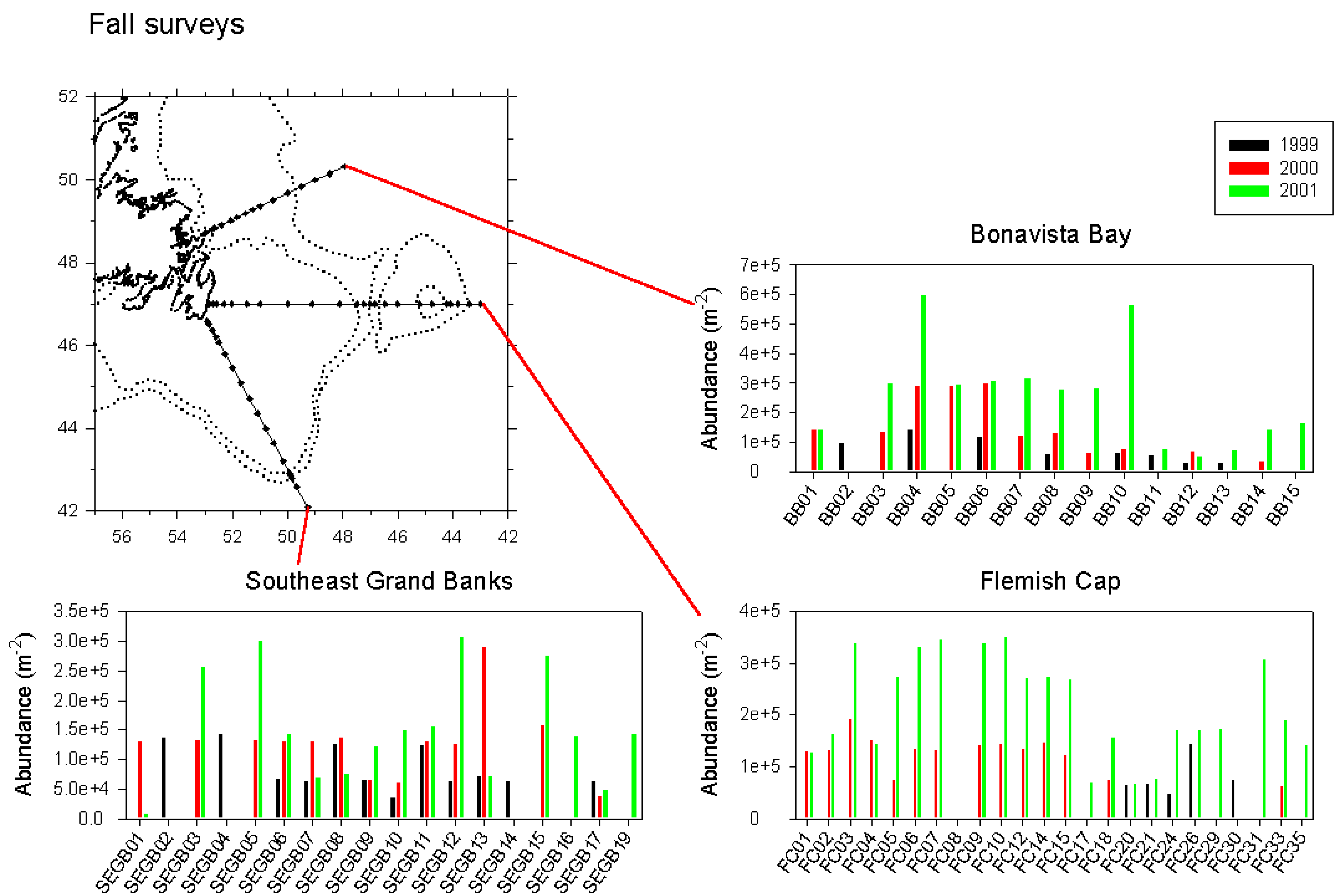

Figure 46. Relative composition of the dominant copepod species during November of 2001. The solid line indicates the total abundance of copepod stages at each site. With the exception of calanoid nauplii, all information presented is based on the abundance of copepodite stages. Station locations are indicated on the corresponding map.

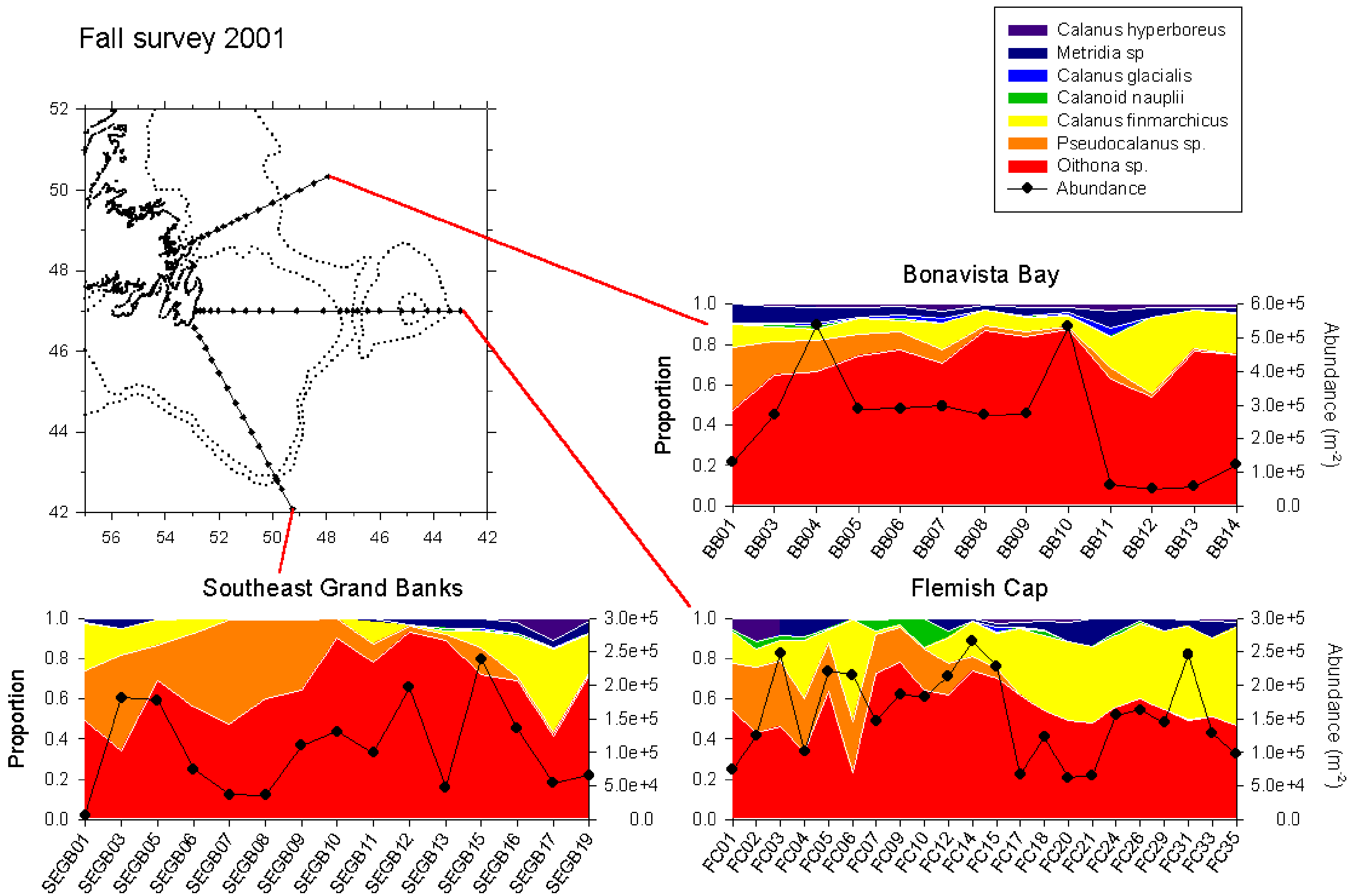

Figure 47. Total zooplankton abundance during spring surveys of the Newfoundland Shelf for the period 2000-2002. Station locations are indicated on the corresponding map. Missing bars indicate that a station was not sampled in a given year and do not indicate the absence of zooplankton at that site.

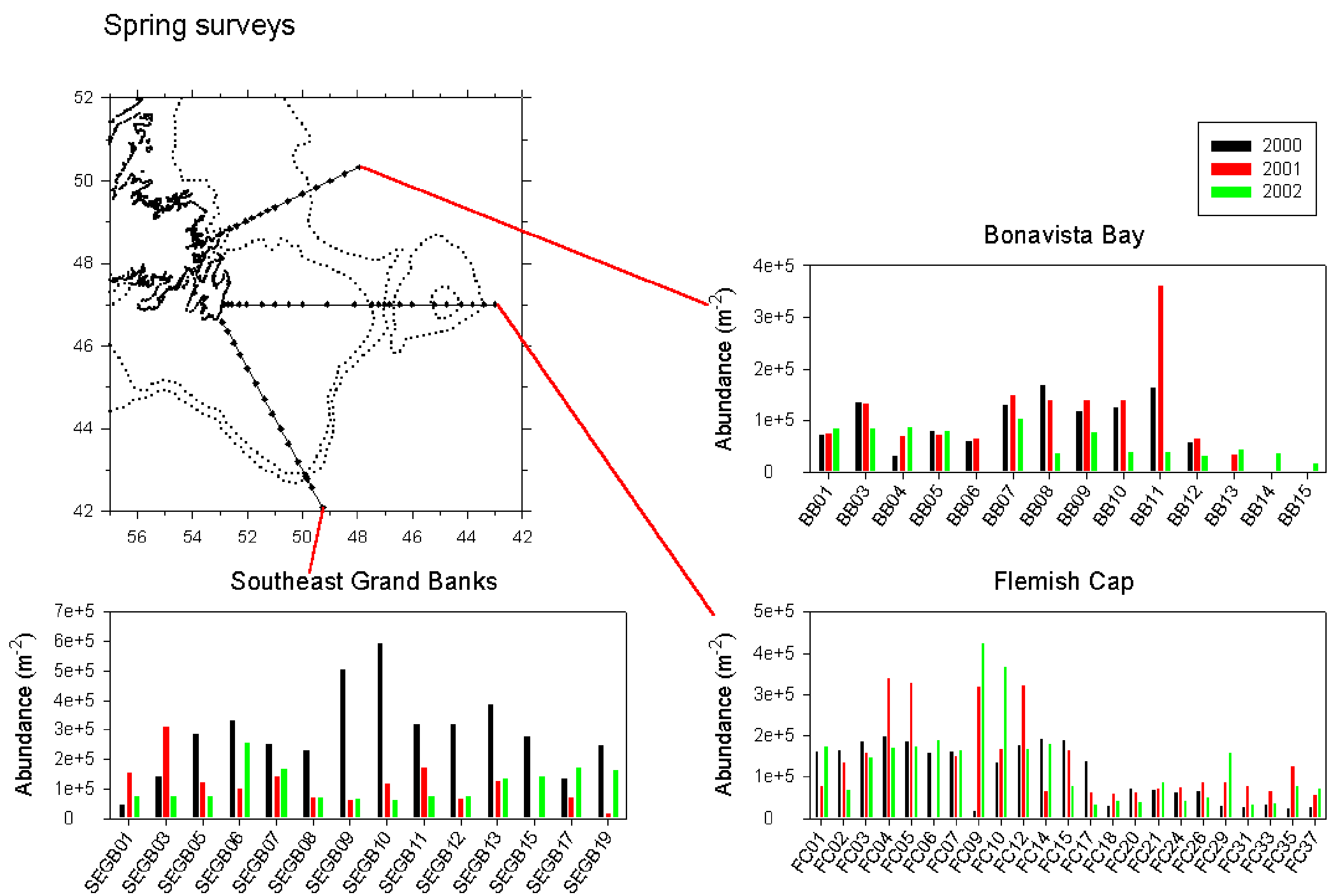

Figure 48. Relative composition of the dominant copepod species during April/May of 2002. The solid line indicates the total abundance of copepod stages at each site. With the exception of calanoid nauplii, all information presented is based on the abundance of copepodite stages. Station locations are indicated on the corresponding map.

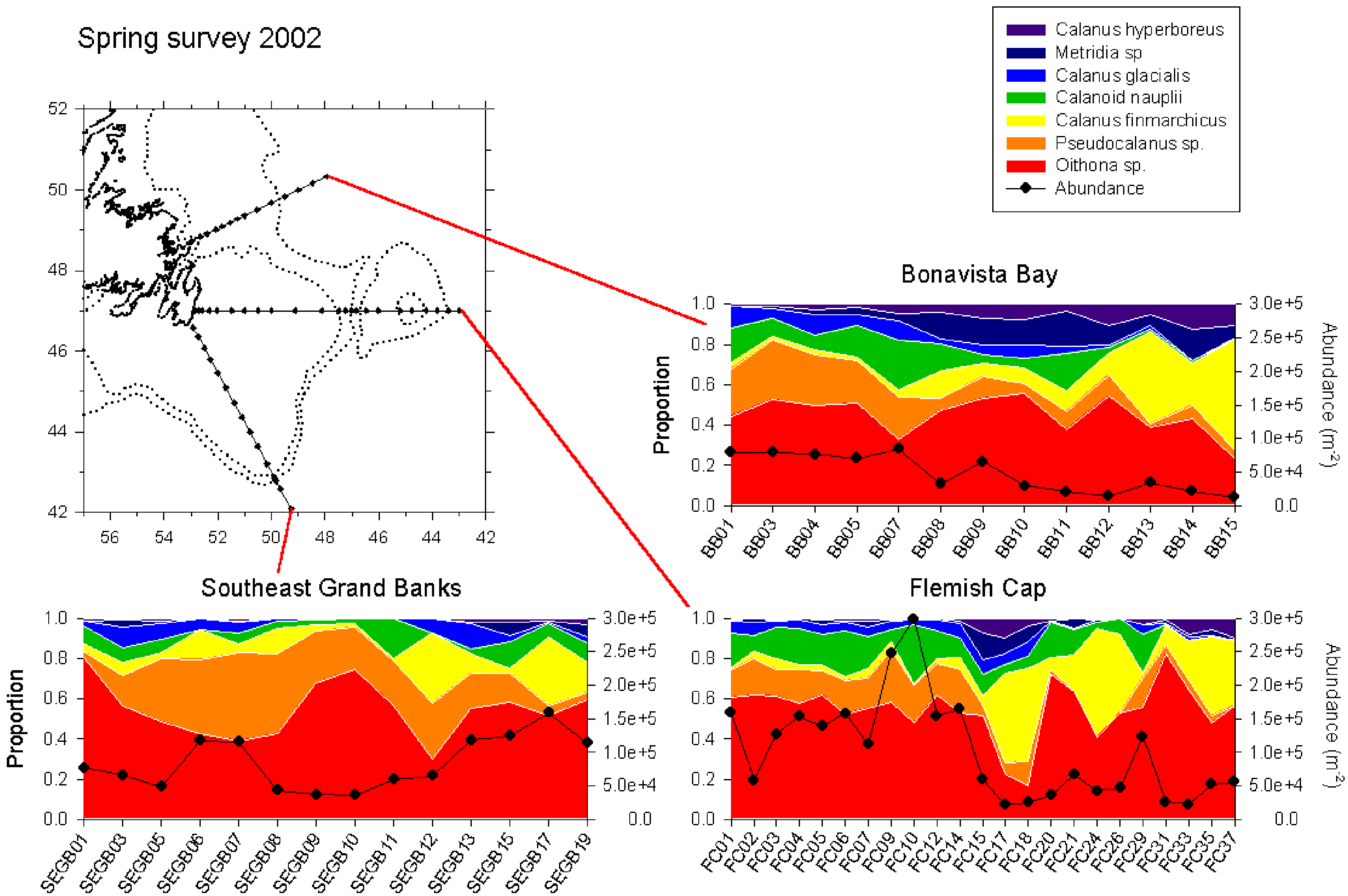

Figure 49. Total zooplankton abundance during summer surveys of the Newfoundland Shelf for the period 1999-2001. Station locations are indicated on the corresponding map. Missing bars indicate that a station was not sampled in a given year and do not indicate the absence of zooplankton at that site.

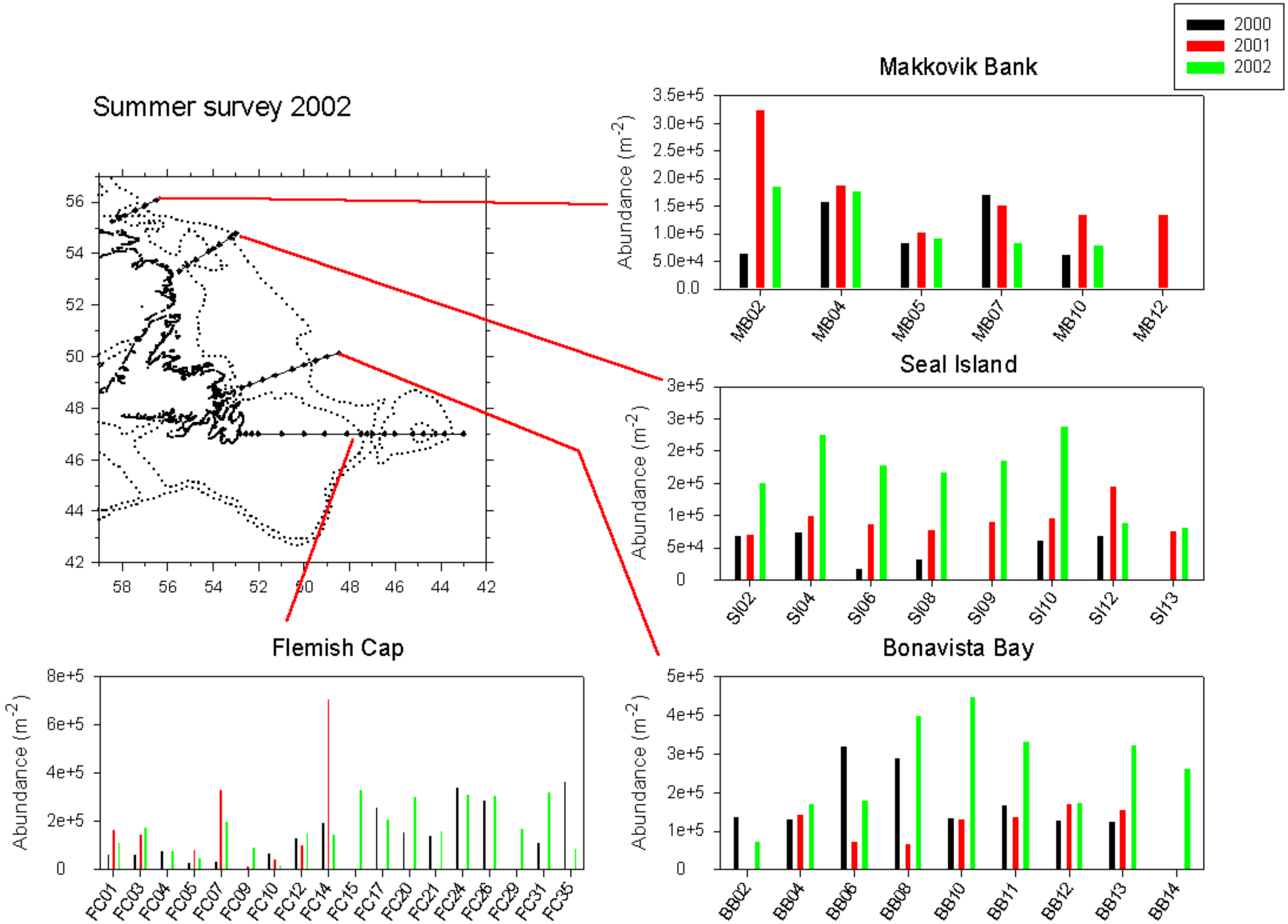

Figure 50. Relative composition of the dominant copepod species during July of 2002. The solid line indicates the total abundance of copepod stages at each site. With the exception of calanoid nauplii, all information presented is based on the abundance of copepodite stages. Station locations are indicated on the corresponding map.