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Biological and Chemical Oceanographic Conditions on the Newfoundland and Labrador Shelf During 2006

Conditions biologiques et chimiques de l'océan sur la plate-forme de Terre-Neuve et du Labrador en 2006

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ABSTRACT

We review the information concerning the seasonal and inter-annual variations in the concentrations of chlorophyll *a*, major nutrients, as well as the abundance of major taxa of phytoplankton and zooplankton measured from Station 27 and along standard transects of the Atlantic Zone Monitoring Program (AZMP) on the Newfoundland and Labrador Shelf in 2006. The inventories of nitrate, the principal limiting nutrient, has remained relatively stable throughout the time series although there appears to be a decline in near-surface levels and an overall reduction in the magnitude of the seasonal cycle in recent years compared to earlier observations. Indications of a decrease in phytoplankton abundance at Station 27 since 2002 were reversed in 2006 but the magnitude of the change is not statistically significant nor was it reflected along the oceanographic transects. In 2006, the overall abundance of zooplankton at Station 27 was low relative to the long term average in 6 of the 12 dominant species groups, including *C. glacialis* and *C. hyperboreus*. In contrast, the abundance of *Calanus finmarchicus* at Station 27 rebounded substantially from its lowest level in the previous year, as did the abundance of euphausiids and *Metridia* spp.. The abundance of the dominant copepod species was at near record levels on both the Newfoundland shelf as well as off the coast of Labrador. The abundance on the northern and southern Grand Banks was generally at or near the lowest levels since 2000.

RÉSUMÉ

La présente étude passe en revue les données sur les variations saisonnières et interannuelles des teneurs en chlorophylle *a* et en éléments nutritifs importants, ainsi que sur l'abondance du zooplancton et du phytoplancton récoltées à la station 27 et le long de transects océanographiques normalisés du Programme de monitorage de la zone atlantique (PMZA) sur le plateau continental de Terre-Neuve et du Labrador, en 2006. Les quantités de nitrate, principal élément nutritif limitatif, sont demeurées relativement stables pendant toute la série chronologique, même s'il semble y avoir une baisse dans les couches proches de la surface et une réduction globale de l'ampleur du cycle saisonnier des dernières années, comparativement aux observations antérieures. La tendance à la diminution de l'abondance du phytoplancton à la station 27 depuis 2002 a été renversée en 2006, mais le changement n'est pas statistiquement significatif et n'a pas été observé le long des transects océanographiques. En 2006, l'abondance générale du zooplancton à la station 27 était faible par rapport à la moyenne à long terme dans 6 des 12 groupes dominants, dont *C. glacialis* et *C. hyperboreus*. Par ailleurs, l'abondance de *Calanus finmarchicus* à la station 27 s'est accrue substantiellement par rapport à son plus faible niveau, l'année précédente, tout comme celle des euphausiacés et de l'espèce *Metridia*. L'abondance de l'espèce dominante de copépodes a presque atteint un niveau record aussi bien sur le plateau continental de Terre-Neuve qu'au large des côtes du Labrador. Sur le nord et le sud des bancs de Terre-Neuve, elle était en général à son plus bas ou presque depuis 2000.

INTRODUCTION

The Altantic Zone Monitoring Program (AZMP) was implemented in 1998 with the aim of increasing DFO's capacity to understand, describe, and forecast the state of the marine ecosystem and to quantify the changes in the ocean physical, chemical and biological properties. A critical element of the AZMP involves an observation program aimed at assessing the variability in nutrients, phytoplankton and zooplankton.

The AZMP derives its information on the state of the marine ecosystem from data collected at a network of sampling locations (fixed point stations, cross-shelf sections, and groundfish surveys) in each region (Quebec, Gulf, Maritimes, Newfoundland) sampled at a frequency of bi-weekly to once annually.

A description of the seasonal patterns in the distribution of phytoplankton (microscopic plants) and zooplankton (microscopic animals) provides important information about organisms that form the base of the marine foodweb. An understanding of the production cycles of plankton, and their interannual variability, is an essential part of an ecosystem approach to fisheries management.

METHODS

We review optical, chemical, selected physical indices, and biological oceanographic conditions on the Newfoundland and Labrador Shelf during 2006. 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 2006 provided reasonable spatial and temporal series coverage of standard variables which provides a foundation for comparison with previous years. Collections and standard variables are based on sampling protocols outlined by the Logistics Steering Committee of the Atlantic Zonal Monitoring Program (AZMP) (Mitchell et al. 2002). Observations presented in this document are based on surveys listed in Table 1.

ANALYSIS

Annual estimates of water column inventories of nutrients, chlorophyll, the mean abundance of key zooplankton species and some physical variables at both the fixed site and as an overall average along each of the four standard transects were based on general linear models (GLMs) of the form

$$Ln(Density) = \alpha + \beta_{YEAR} + \delta_{MONTH} + \varepsilon$$

for the fixed station, where *Density* is in units of m^{-2}, α is the intercept, β and δ are categorical effects for year and month effects, and ε is the error, and

$$Ln(Density) = \alpha + \beta_{YEAR} + \delta_{STATION} + \varepsilon$$

for each of the transects and seasons, where δ takes into account the effect of station location. Density, either in terms of numbers or biomass, is log-transformed to deal with the skewed distribution of the observations. Physical variables, inventories of nutrients and chlorophyll were not transformed. To derive an estimate of the inter-annual variations based on all occupations of the transects, a full model which includes seasonal effect is applied

$$Ln(Density) = \alpha + \beta_{YEAR} + \delta_{STATION} + \gamma_{SEASON} + \varepsilon$$

An estimate of the least-squares means based on type III sums of squares is used as the measure of the overall year effect.

SATELLITE REMOTE-SENSING OF OCEAN COLOUR

Phytoplankton biomass was also estimated from ocean colour data collected by the Moderate Resolution Imaging Spectroradiometer (MODIS) "Aqua" sensor (http://modis.gsfc.nasa.gov/). The MODIS data stream began in July, 2002. The composites and statistics from MODIS used in this report are only provisional since they have not yet been intercalibrated with the SeaWiFS imagery. Satellite data do not provide information on the vertical structure of phytoplankton in the water column but do provide highly resolved (~1.5 km) data on their geographical distribution in surface waters at the large scale. Bi-weekly composite images of surface chlorophyll for the entire NW Atlantic (39-62.5 N Lat., 42-71 W Lon.) are routinely produced from SeaWiFS/MODIS data (http://www.mar.dfo.mpo.gc.ca/science/ocean/ias/seawifs/seawifs_1.html). Basic statistics (mean, range, standard deviation, etc.) are extracted from the composites for selected sub-regions. We report on the available time series of mean surface chlorophyll *a* levels at selected sub-regions on the Newfoundland and Labrador Shelf (Fig. 1).

CONTINUOUS PLANKTON RECORDER (CPR) SURVEY

The Continuous Plankton Recorder (CPR) Survey[1] provides an assessment of long-term changes in abundance and geographic distribution of planktonic organisms ranging from phytoplankton cells to larger macrozooplankton (Warner and Hays 1994; Richardson et al. 2006). CPR collections in the northwest Atlantic began in 1959 and continued with some significant interruptions during the latter period through till 1986. Because of the inconsistency in seasonal coverage, we only discuss the data for the period up to 1978 for the earlier part of the series. Collections were renewed in 1991 and continue to present. The recorder is towed by ships of opportunity along a number of standard routes throughout the North Atlantic. The CPR device collects plankton at a nominal depth of 7m through an aperature and organisms are retained on a moving band of silk material and preserved. Sections of silk representing 18.5 km tow distance and ca. 3 m^3 of water filtered are analyzed microscopically using standard methods since the inception of the program thereby allowing valid comparisons between years. Every second section is analyzed providing a horizontal scale of ca. 37 km. The CPR taxon categories varied from species to subspecies, while others are identified at coarser levels such as genus or family. Throughout this report, we use the same level of identification of each taxon as provided in the original microscopic analysis. Data are available approximately one year after collection, therefore we are limited to 2005 data in this report. The CPR taxa evaluated in this report included the dominant assemblages of phytoplankton, microzooplankton, an important macrozooplankton prey and predator species. We did not differentiate the data based

[1] See SAFHOS web site at (http://192.171.163.165/) for a description of the CPR Program collected for The Sir Alister Hardy Foundation for Ocean Science of Plymouth, England.

on bathymetry (e.g. shelf versus slope) and included all the data bounded by the NAFO Divisions 3LMNO3Ps (Fig. 1).

FIXED STATION – SEASONAL AND INTER-ANNUAL VARIABILITY IN WATER COLUMN OPTICS, SOLAR RADIATION, AND WATER COLUMN STRUCTURE

The availability of light for photosynthesis in an aquatic ecosystem is determined by the penetration of light (Kirk 1994), expressed as the vertical attenuation coefficient (K_d), which is determined by dissolved and coloured substances and particulate matter in seawater. The vertical attenuation coefficient (K_d) were derived from in-water light extinction measurements using a CTD-rosette mounted PAR (photosynthetic active radiation) meter. The downward vertical attenuation coefficient of PAR ($K_{d\text{-}PAR}$) was estimated from the linear regression of $\ln(E_d(z))$ versus depth z (where $E_d(z)$ is the value of downward PAR irradiance at z m) in the depth interval from near surface to 50 m. When in-water PAR data were not available, the vertical attenuation coefficient was calculated by:

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

where B(z) is the concentration of chlorophyll *a* in mg m^{-3} (we substitute calibrated chlorophyll *a* from *in-situ* chlorophyll *a* fluorescence when discrete concentrations were not available) at depth z meters. The additional coefficients in this equation are related to the components of pure seawater and dissolved substances. The average value of K_d was calculated for the upper water column using the chlorophyll *a* profile in the upper 50 m.

The vertical light attenuation at Station 27 was generally lower in 2005-06 compared to observations in previous years (Fig. 2). The peak in the vertical attenuation coefficient that coincides with the timing of the spring bloom was elevated in 2006 compared to 2005. The duration of the peak in light attenuance in 2006 was also reduced in contrast to previous years but, background levels and the timing of the maximum were consistent with earlier values. The seasonal cycle in light attenuance in 2006 was generally consistent with previous years with the exception of substantially lower levels observed in April. As a result of lower light attenuance levels observed in 2005-06, euphotic depths were generally deeper (60-80 m) and less variable compared to the earlier time series. The seasonal cycle in euphotic depth shows a corresponding minimum (20-30 m) during April related to the development of the spring phytoplankton bloom while deeper levels of 60-70 m are observed during the post-bloom periods. We suggest some caution overall in the interpretation of any given time series since we may not capture the full dynamic range of the series as a result of the availability of occupations which can vary from year to year depending on the availability of ships.

Although there are differences in the timing of the seasonal cycle among years, the GLM estimate of annual mean attenuance of light (K_d) and euphotic depth (Z_{eu}) do not show any statistically significant inter-annual variations. For both optical measures, there are indications of a decreasing trend in annual means of K_d since 2000 (corresponding upward trend in Z_{eu} since attenuance and photic depths are inversely related), with the lowest value of the time series occurring in 2005 (Fig. 6).

Time series and seasonal development of mixing properties at Station 27 in 2006 were generally consistent with previous years (Fig. 3). Seasonal development of upper water stratification peaks during late summer reaching 0.07 kg m^{-4}, while the mixed-layer shallows to 10-20 m. There is some indication of a gradual increase in maximum stratification at Station 27 during August since 2003. Maximum mixed-layer depths occur during January reaching near full water column depths (~176 m) in most years. Seasonal stratification was notably higher in 2006 compared to the long-term mean (1993-2005) during late spring through autumn. Similarly, mixed-layer depths in 2006 were below normal in late autumn but substantially deeper during winter.

Mean annual estimates of the mixed-layer depth showed statistically significant ($p<0.05$) inter-annual variations trending upward since a low value in 2000 of ca. 45 m and peaking in 2004 at ca. 70 m, and declining again in 2005-06 (Fig. 6). In contrast, no significant inter-annual variability was observed in the stratification index during this period.

FIXED STATION – SEASONAL AND INTER-ANNUAL VARIABILITY IN PHYTOPLANKTON AND NUTRIENTS

Vertical profiles of chlorophyll *a* at Station 27 continue to vary in terms of the magnitude and duration of the spring bloom (Fig. 4). Near-surface chlorophyll *a* levels were unusually low throughout the spring bloom in 2005 in contrast to a more intense bloom in 2006 comparable in magnitude to levels observed previously (Fig. 4). We use the criteria of integrated chlorophyll *a* levels ~100 mg m^{-2} in upper 100m to define start and end times of the phytoplankton bloom. The initiation of the bloom in 2006 was detected by mid-April with integrated concentrations in excess of 300 mg m^{-2} although we estimated the initiation of surface blooms on the southeastern Grand Banks around mid-March based on the progression of the bloom in previous years and MODIS Satellite Colour Imagery. Although chlorophyll *a* inventories in the upper 100 m at Station 27 were substantially greater in 2006 in contrast to 2005, the duration of the bloom was limited at ca. two weeks compared to 4-6 weeks observed in previous years. There was evidence of small accumulations of phytoplankton biomass beyond the spring bloom again in 2006 (i.e. short-term summer and autumn blooms), a pattern consistent with observations during earlier years. There is an indication that there are significant concentrations of phytoplankton biomass below 50 m again in 2006, presumably as a result of the sinking of larger diatom cells, the main phytoplankton of the spring bloom.

Although there are differences in the timing of the seasonal cycle among years, the GLM estimate of mean chlorophyll inventories (0-100 m integral) do not show any statistically significant inter-annual variations. There are indications of a decreasing trend in the annual mean since 2000, varying between ca. 50–100 mg m^{-2} with the lowest value of the time series occurring in 2005 (Fig. 6).

The vertical distributions of the inorganic nutrients (nitrate, silicate, and phosphate) included in the observational program of the AZMP show strong seasonal covariation (Petrie et al. 1999). For this reason, and because the availability of nitrogen is hypothesized to be limiting to the growth of phytoplankton in the NW Atlantic and supported by our *in-situ* observations, more emphasis in this report will be placed on variability in nitrate concentrations.

The vertical structure of nitrate (combined nitrate and nitrite, hereafter referred to as nitrate) shows dynamic seasonal changes in the water column at Station 27. Concentrations of nitrate were typically >3 mmol m^{-3} throughout the water column and approached maxima of 10 mmol m^{-3} near the bottom prior to the spring bloom (Fig. 5). Subsequently, concentrations of nitrate were depleted in the upper 50 m to <0.5 mmol m^{-3} and remained relatively low throughout the summer. Notably absent in 2006 were the periodic intrusions of nitrate from depth that have been observed during earlier years. Nitrate concentrations remained very low ($\leq$1 mmol m^{-3})

throughout the year in the upper water column until very late in the year when nutrient replenishment occurred. Deep water concentrations of nitrate shoaled during August-September as observed in previous years, coincident with the annual minima in water column salinity from ice-melt further north.

Time series of nitrate inventories at Station 27 showed differences between years (Fig. 5). Nitrate inventories in the upper 50 m showed expected seasonal trends with winter and fall maxima, rapid depletion during the spring bloom, and occasional periodic intrusions during the late summer – early autumn (Fig. 5). 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. Nitrate inventories in the upper layer continue to show a gradual reduction consistent with the decline observed since the start of the AZMP (Fig. 5). The cause for the decline in shallow inventories of nitrate remains unknown, but may be linked to changes in productivity, water column structure, and influence of volume transport of the inshore branch of the Labrador Current. The deep water inventories are relatively stable throughout the time series.

High seasonal variability characterizes nitrate inventories in the upper 50 m water column (depth zone over which nutrient dynamics are strongly influenced by biological processes) at Station 27 (Fig. 5). Winter maximum nitrate inventories in the upper 50 m at Station 27 in 2006 were slightly lower compared to earlier years. Although the summer and fall 2006 nitrate levels were similar to previous years, the winter and spring levels in the upper water column were also substantially below the long-term mean. The deep water (50-150 m) inventories of nitrate have remained relatively stable throughout the time series although there appears to be a general weakening of the seasonality in recent years compared to earlier observations. The seasonal cycle of deep nitrate inventories which is normal relatively stable throughout the year showed some differences during 2006 compared to earlier years (Fig. 5). This may be having an impact on overall phytoplankton production because we have observed a gradual decline in standing stocks and duration of blooms in recent years. Although we have observed a gradual reduction in nitrate inventories in the shallow layer since 2000, the seasonally-adjusted mean annual estimate was not significant ($p>0.05$). The deep water inventories also declined during 2000 to 2003 but, have been increasing gradually during recent years and did not vary inter-annually (Fig. 6).

OCEANOGRAPHIC SECTIONS - SEASONAL VARIABILITY IN LIMITING NUTRIENTS AND PHYTOPLANKTON BIOMASS

The vertical distribution of nitrate and chlorophyll *a* have varied seasonally and spatially across the standard AZMP sections since the inception of the program. Vertical distributions of nitrate were mainly depleted (<1 mmol m^{-3}) in the upper 50 m along all sections during occupations in spring 2006 and prominent shoaling of the nutricline in the offshore was evident (Fig. 7). Sub-surface and near-surface chlorophyll *a* concentrations during the spring 2006 survey were elevated compared to previous years over much of the Grand Banks and Newfoundland Shelf. The location of the offshore branch of the Labrador Current and slope water regions were characterized by elevated concentrations of nitrate along all sections, presumably being influenced by the North Atlantic waters rich in inorganic nutrients and characterized by enhanced vertical mixing.

The summer occupations across the northeast Newfoundland and Labrador sections are typically characterized by further depletion of nitrate concentrations to <1.0 mmol m^{-3} in the upper water column from levels observed during the spring occupations (Fig. 8). There was evidence of depletion in nitrate concentrations, but this varied in the extent of depth by location of the section. The largest vertical extent in biological uptake of nitrate occurred along the extent of the Flemish Cap, and to a more-limited extent along the inner Shelf of the Seal Island section, extending to depths of ca. 50 m. Shoaling of the nitracline was also evident from the inshore to offshore areas over all sections, which is consistent with conditions observed in earlier years. The summer 2006 concentrations of chlorophyll *a* were comparable across the Newfoundland Grand Banks and Labrador Shelf sections to previous years. Evidence of episodic or localized sub-surface phytoplankton blooms were observed along all sections (Fig. 8). MODIS satellite colour imagery confirmed low surface chlorophyll *a* levels across the Newfoundland and Labrador Shelf sections (Fig. 11).

Enhancement of nitrate distributions were apparent along the central and northern sections, while being less pronounced across the entire SE Grand Banks section during the autumn occupations (Fig. 9). Despite the depletion of nitrate in the upper water column, increased biological activity was evident along all sections from near-surface to depths in excess of 50 m, indicating the occurrence of autumn phytoplankton blooms in these areas in 2006, somewhat greater than has been observed in previous years.

The generalized linear models generally show that within season, variables that describe the upper water column (stratification, inventories of chlorophyll and nitrate) show significant inter-annual variations (Table 2). The exceptions tend to be associated with many of variables during the summer, particularly along the Bonavista Bay and Seal Island transects. Nitrate inventories in the shallow (0-50 m) and deeper layers (50-150 m) show less inter-annual variability, particularly in the fall, but there are significant inter-annual variations in deep water nutrient inventories in the spring across the Grand Banks with the exception of the northeast Newfoundland Shelf and the southern Labrador Shelf during summer (Table 2). Despite statistical significance, partly because of the overall accuracy of the surveys and consistent spatial patterns in the distribution of water masses, there are no consistent overall trends in optical (K_{d_PAR}, Z_{eu}), chlorophyll *a* inventories, or stratification among the four oceanographic transects (Fig. 10). An exception to this general pattern is the weakening in the seasonal cycle of shallow water inventories of nitrate across the transects, and downward trend in deep water inventories along the Seal Island during summer in recent years. One must be particularly careful in the interpretation of inter-annual variations in chlorophyll and nutrient inventories from the spring surveys because differences in the timing of the cruises relative to that of the biological production cycle can lead to aliasing. The rise (2000-03) and fall (2004-05) in spring chlorophyll concentrations along the Southeast Grand Banks, Flemish Cap and Bonavista Bay transects (and vice versa for surface inventories of nitrate) indicate that timing of the spring phytoplankton bloom, relative to the timing of our surveys, moved from an early to a later and back to an earlier date during the six year period. The median date of the surveys varied by 10 days, with 2004 being the earliest (days 107-122) and 2005 being the latest (days 120-129): from 2001 to 2004 the median date of the survey varied by only three days.

REMOTE SENSING OF OCEAN COLOUR

Satellite ocean colour (SeaWiFS and MODIS) data can provide large-scale images of surface phytoplankton biomass (chlorophyll *a*) over the whole of the NW Atlantic to enhance temporal and spatial coverage not possible based upon conventional sampling with vessels. Using a two-week composite image of the Newfoundland and Labrador regions supplements our ship-based observations and provides seasonal coverage and a large-scale context with which to interpret our limited survey data (Fig. 11). The MODIS ocean colour imagery provides information about the timing and spatial extent of the spring bloom which can vary from year to year across the Grand Banks and northeast Newfoundland Shelf. The enhanced surface chlorophyll *a* concentrations observed along the spring 2006 sections, particularly around the Flemish Cap and on the northeast Newfoundland Shelf, was confirmed by MODIS imagery. In addition, the limited duration (ca. 2 weeks) of the spring phytoplankton bloom within the Avalon Channel (Station 27) was supported by the composite imagery showing low background chlorophyll *a* levels in this region in 2006 by early May. Similarly, the patchy distribution of near-surface chlorophyll *a* concentrations across the sections and higher surface concentrations restricted to the northern sections (White Bay and Seal Island) during the summer 2006 survey was also supported by MODIS composite imagery. The summer 2006 colour imagery also indicated extensive surface phytoplankton blooms across the central Labrador Sea. Extensive cloud cover observed in the autumn of 2006 did not permit valid comparisons of our *in-situ* data with satellite imagery, which is one of the principal limitations of remote sensing in northern regions.

At larger scales, the statistical sub-regions in Newfoundland and Labrador indicate the magnitude of surface phytoplankton blooms were in general higher in 2006 compared to 2005, this was particularly evident for the southern and central sub-regions (Fig. 12). The occurrence of autumn blooms which is sometimes not captured by conventional sampling within the region, is supported by MODIS imagery across the Grand Banks, Newfoundland and Labrador Shelf. The satellite data also indicate that the highest surface chlorophyll *a* concentrations of 2-3 mg m^{-3} are confined to the southern and eastern portion of the Grand Banks (e.g. southeast Shoal and Flemish Pass sub-regions) compared to lower levels (typically < 2 mg m^{-3}) observed elsewhere. The temporal trends since 2002 indicate that the spring bloom is progressing earlier over many of the sub-regions with the exception of the most northern sites (e.g. Hudson Strait and Northern Labrador Shelf).

CONTINUOUS PLANKTON RECORDER (CPR)

The CPR survey provides retrospective observations of the distribution and relative abundance of plankton in the NW Atlantic to complement more recent observations as part of the AZMP. CPR data lags AZMP information by one year thereby only CPR data up to 2005 are currently available. The phytoplankton colour index (PCI) and the abundance of dinoflagellates have increased during the available time series (Fig. 13). The spring bloom is typically dominated by diatoms in the Newfoundland and Labrador region which have remained relatively stable. The magnitude and seasonal cycle of phytoplankton abundance also remained relatively stable with the exception of dinoflagellates during 1991-2004 which shifted to earlier months compared with the 1960-70's, but, was not reflected in the patterns observed in 2005. Although the timing of peak abundance did not change, there appeared to be a systematic increase in the PCI and relative abundance of diatoms in 2005 during winter and spring compared to earlier decades. Examination of trends in selected (considered dominant based on recent AZMP results) CPR zooplankton indicated the dominant calanoid and cyclopoid copepods have generally declined from the 1960-70's to the recent decade (Fig. 14). Similar trends have been observed for some of the larger macrozooplankton such as the Euphausiacea which declined throughout the NW Atlantic during the 1990-2000's. The early stage development for copepods (nauplii) and hyperiid amphipods have increased slightly during the recent decade compared to the earlier period but these taxa have also tended to decline steadily since the mid-late 1990's. Although the timing of peak abundance did not change dramatically in any of the selected CPR taxa, there appeared to be an increase in 2005 during the seasonal cycle of early (CI-CIV) and late (CV-CVI) stages of calanoid copepods, *Temora* spp., and Euphausiacea (Fig. 14).

FIXED STATION - ZOOPLANKTON

There was relatively strong seasonality in the overall abundance of both *Calanus finmarchicus* and *Pseudocalanus* spp. at Station 27 in 2006 in contrast to the previous two years, marked by a strong peak in late spring/early summer, although the seasonal progression of stages was similar to previous years (Fig. 15). The seasonal cycle of other copepod species was similar to observations from previous years (Fig. 16). Larvaceans appear to show two peaks in abundance, one following the spring phytoplankton bloom, and another in the fall (data were missing for fall 2006) while the pattern of seasonality for pelagic gastropods and euphausiids generally shows a gradual increase, often peaking in mid to late summer (Fig. 16). A generalized linear model which included the effects of year and month, as categorical variables, was used to estimate inter-annual variations in the overall abundance of the 12 dominant zooplankton taxa present at Station 27. Analytical results indicated that all species demonstrate a statistically significant seasonal cycle of abundance based on type III sums of squares (i.e. the sums of squares obtained by fitting each effect after all the other terms in the model). However, only four of the twelve species showed significant inter-annual variations in overall abundance (*C. glaicialis*, *Metridia* spp., *Pseudocalanus* spp., *Temora longicornis*) (Fig. 17). The abundance of *Calanus glacialis, C. hyperboreus,* and larvaceans were at or near the lowest value recorded since 1999. In contrast, the abundance of *C. finmarchicus*, *Metridia* spp., and euphausids appeared to increase substantially in 2006, following general periods of decline since 2002/03. The generalized linear model which included year and month effects explained 37% to 91% of the overall variance in log-transformed abundance of the zooplankton taxa (mean 61%). Over the 1999-2006 observation period, most taxa exhibited approximately a 3-fold variation in abundance in average annual abundance.

The seasonal pattern in the relative distribution of copepod biomass among the eight dominant species at this site was not strongly different in 2006 from the pattern in previous years (Fig. 18). It is notable that the relative contribution of *C. hyperboreus* during the spring of 2006 was generally lower than previously observed, although the relative abundance was comparable to values seen in 1999 and 2000. However, throughout most of the year, the copepod biomass at Station 27 was dominated by *C. finmarchicus* or one of its sister species (either *C. glacialis* or *C. hyperboreus*). There was significant inter-annual variation in total copepod biomass at Station 27 ($F_{III}[7,232] = 2.72$, $p = 0.01$), with biomass in 2002 being significantly greater than levels observed in other years (Fig. 19)

OCEANOGRAPHIC SECTIONS - ZOOPLANKTON

The seasonally-adjusted mean abundance of the dominant copepod species showed important north-to-south differences in the significance of inter-annual variations. Along the southeast Grand Banks transect, which is surveyed only in the spring and fall, only large calanoid nauplii and *Metridia* spp. exhibited statistically significant inter-annual variations, with the former showing high abundances in 2000 and 2005 while the latter was notably lower in 2006 (Fig. 20). The remaining five taxa (*C. finmarchicus, C. glacialis, C. hyperboereus, Oithona* spp., and *Pseudocalanus* spp. showed fluctuations in abundance that were not statistically different among years. Despite the lack of statistical significance, most of these five taxa were at or near their lowest abundance since 2000.

The abundance of copepods along the Flemish Cap transect showed a little more variability than on the southeast Grand Banks. All taxa, with the exception of *C. hyperboreus*, showed significant inter-annual variations in abundance. In contrast with the southeast Grand Banks, the abundance of all seven taxa in 2006 was at or near their highest seasonally-adjusted abundance levels since 2000.

Our observations from the Bonavista Bay transect, which is sampled three times per year, showed that five of the 7 dominant copepod taxa exhibited statistically significant inter-annual variations in abundance based on the GLM (Fig. 20). Only in the case *Pseudocalanus* spp. and large calanoid nauplii were inter-annual variations in abundance not statistically resolvable. In previous years, *Pseudocalanus* spp. had exhibited significant inter-annual variability, but additional information from 2006 showed that the pattern of variations could not be distinguished from the influence of seasonal or spatial factors. However, in all taxa, with the exception of *Metridia* spp. and *Pseudocalanus* spp., the abundance in 2006 was at (or very near) the highest levels recorded since the inception of the AZMP.

Although copepod abundance along the Seal Island transect, which is sampled only in July, is generally higher than the long term AZMP average, all three *Calanus* species, along with *Metridia* spp. and *Pseudocalanus* spp. have shown slight decreases in the last one or two years (Fig. 20). In all but one taxa (*C. hyperboreus*), abundances showed statistically significant inter-annual variations. Most species showed a slight decline from abundances recorded in 2004 (or 2003 for *C. hyperboreus*) but in most instances the decrease was not statistically significant. In the case of *C. finmarchicus*, the abundance in 2005 was nearly 19 times higher than the lowest levels recorded in 2000. Most other species showed a 4 to 9-fold variation in overall abundance among years.

We did not detect any substantial variations in the spatial distribution of either abundance or biomass during either the fall of 2005 (Fig. 21) or the 2006 spring (Fig. 22) or summer (Fig. 23) surveys. Sorting of zooplankton samples from the 2006 fall survey was incomplete at the time of the meeting. There were subtle variations, but the general patterns of distribution in 2005 were similar to the average for 2000-04. In most instances for 2005, the seasonal patterns in abundance along each transect was similar to that observed in previous years (results not shown).

Variations in abundance tended to be more substantial (i.e. significant) than variations in estimated biomass (Table 3).

DISCUSSION

Overall, the seasonality of chemical and biological variables at Station 27 and along the major AZMP sections in 2006 was similar to previous years (1999-2005). 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 program but in contrast to 2001 when the onset of the spring phytoplankton bloom was delayed. However, satellite information indicates the onset of the spring bloom, at least since 2002, has become gradually earlier throughout the region of the Newfoundland Shelf and Labrador Sea.

There were a few notable trends in the observations from Station 27 and the oceanographic transects. At Station 27, the integrated seasonally-adjusted chlorophyll inventory along with many zooplankton species (*C. glacialis, C. hyperboreus, Oithona* spp., and larvaceans) were are low levels relative to the overall time series of observations. Exceptions to this trend were *C. finmarchicus*, *Metridia* spp. and euphausids, which all showed substantial increases in abundance relative to 2005. Few of these trends were statistically significant, largely as a result of the considerable sampling variability. The deep (0-150 m) inventories of nitrate and silicate were similar to 2005 but levels are still low relative to 2000. However, the trends observed at Station 27 were in marked contrast with those observed along the oceanographic transects. With the exception of a general decline in the seasonally-adjusted deep (50-150 m) silicate inventory along the most transects, few of the standard oceanographic variables showed significant trends during the period 2000-06. Values in 2006 were generally near the overall mean since the inception of AZMP. In addition, most of the seven major copepod taxa along the Flemish Cap, Bonavista Bay and Seal Island transects were either at or near their maximum seasonally-adjusted means, in contrast to patterns at Station 27. Zooplankton abundance along the Southeast Grand Banks showed few significant trends, but there was indication that many species were at their lowest levels since 2000.

Discrepancies between the patterns of seasonally-adjusted means for oceanographic variables and major zooplankton taxa between Station 27 and the oceanographic transects is in marked contrast with the relatively large decorrelation scales found in temperature and salinity (Mathieu et al. 2003). One possible explanation is that the decorrelation scale is relatively small (10s of kms) for chemical and biological variables collected by the AZMP because local coastal processes are highly dynamic in contrast to broad oceanographic bio-physical interactions that govern the patterns of abundance further on the shelf. An analysis of the correlation between observations at Station 27 and transect stations taken during oceanographic surveys shows that the average correlation, based on the seven dominant copepod taxa, is highest for the nearshore stations along the Bonavista Bay and Flemish Cap transects, after which it drops rapidly as one moves offshore (Fig. 24). There is no correlation with conditions at the deep water offshore stations, and a nearly inverse relationship with conditions along the Seal Island transect. The high concentration of copepods in offshore waters may therefore have a strong influence on the mean abundance estimated from the GLM analysis.

Aliasing of sampling and the onset of the spring phytoplankton bloom are likely to prevent an estimation of the annual mean phytoplankton standing stock from the oceanographic surveys. Estimates of annual mean phytoplankton standing stock or surface nutrient inventories along oceanographic transects based on GLM analysis are highly influenced by the magnitude of the spring phytoplankton bloom observed during our surveys. However, attempts to derive average annual values were strongly influenced by the stage of the spring phytoplankton bloom, as determined from the relative abundance of nutrients and phytoplankton. In some years (e.g. 2003), phytoplankton standing stock was low during the spring oceanographic surveys whereas the surface nitrate inventory was high, while the opposite was true in 2000.

The two-week composite estimates of surface chlorophyll do assist in the interpretation of these patterns but a more temporally-resolved estimate of the seasonal variations in surface chlorophyll throughout the entire Atlantic Zone would assist in determining the degree of inter-annual variation in both the magnitude and duration of the spring phytoplankton bloom. Combining the data from the oceanographic surveys with satellite observations could enable us to obtain a three-dimensional view of the progression of phytoplankton dynamics throughout the Zone and thus provide a more accurate estimate of changes in standing stock.

The most notable advance in 2004 was in our ability to provide quantitative analysis of inter-annual differences in the abundance of dominant zooplankton taxa at Station 27 and along the key oceanographic transects (Pepin et al. 2005). The analytical approach is somewhat simplistic and does not take into consideration of major shifts in the spatial distribution of species (this appears as part of the error). However, the approach has revealed significant inter-annual variations in the abundance of zooplankton on the Shelf. The approach based on general linear models to determine the inter-annual variations in abundance of taxa from AZMP collections did raise some questions about the programs overall ability to accurately monitor zooplankton abundance and species composition. Data from Station 27 revealed that only 12 taxa were sufficiently abundant and frequent to allow appropriate inter-annual comparison in abundance patterns, which included copepods, gastropods, larvaceans and euphausiids. In contrast, only 7-8 species of copepods were sufficiently abundant and frequent on the shelf to allow effective and reliable intercomparison throughout the AZMP implementation period. Other groups, such as bivalves, gastropods, euphausiids and larvaceans were highly patchy in their distribution, making statistical intercomparisons unfeasible at this time. Longer time series of observations may be required before we can detect significant inter-annual variations in abundance based on the AZMP survey design and collection methods. We did investigate the potential to simply contrast seasonal and inter-annual variations in abundance without taking into consideration the spatial distribution of each species. This did allow a greater number of species to be included in the analysis but the complexity of the results requires further investigation at this time before we feel that we can comment on the overall trends.

ACKNOWLEDGMENTS

We thank Wade Bailey, Eugene Colbourne, Joe Craig, Charlie Fitzpatrick, Dave Senciall, and Paul Stead for their assistance at sea. We also wish to thank the many scientific assistants (Robert Chafe, Frank Dawson, Trevor Maddigan, Scott Quilty, Maitland Sampson, Dave Sears, Marty Snooks, and Keith Tipple) aboard ships of opportunity who assisted with field collections. The expertise of Gerhard Pohle, Cynthia McKenzie and Mary Greenlaw was crucial to the completion of this work.

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Table 1. Listing of AZMP Sampling Missions in the Newfoundland and Labrador Region in 2006. The transects are Southeast Grand Banks (SEGB); Flemish Cap (FC); Trinity Bay (TB), Bonavista Bay (BB); Funk Island (FI); White Bay (WB); Seal Island (SI), 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, zooplankton, and including partial occupations) profiles provided for each seasonal section and fixed station occupations.

Mission ID	Dates	Sections/Fixed	# Hydro Stns	# Bio Stns
TEL670	Apr 22-May 2, 2006	SEGB, FC, BB, FI	71	61
WT675	Jul 25-Aug 7, 2006	FC, BB, WB, SI	75	49
HUD731	Nov 18-Dec 5, 2006	SEGB, FC, BB, TB	71	47
Fixed	Jan-Dec 2006	Station 27	45	18

Table 2. Seasonal significance levels of the year effect for the stratification index, and inventories of chlorophyll (0-100 m integral) and nitrate (0-50 m and 50-150 m integrals), vertical light attenuance and euphotic depth based on the results of the generalized linear model that included year and station identifier as categorical variables during 2000-06. ns = not significant

Stratification	Spring	Summer	Fall
Southeast Grand Banks	0.0001		0.0001
Flemish Cap	0.0001	0.01	0.0001
Bonavista Bay	0.0001	0.0001	0.02
Seal Island		0.05	
Chlorophyll (0-100 m)			
Southeast Grand Banks	ns		0.0001
Flemish Cap	0.02	0.01	0.0001
Bonavista Bay	0.0001	ns	0.0001
Seal Island		ns	
Surface Nitrate (0-50 m)			
Southeast Grand Banks	0.0001		0.02
Flemish Cap	0.0001	0.05	0.01
Bonavista Bay	0.0001	ns	0.0001
Seal Island		ns	
Deep Nitrate (50-150 m)			
Southeast Grand Banks	0.0001		ns
Flemish Cap	0.0001	0.0001	ns
Bonavista Bay	ns	0.01	ns
Seal Island		ns	
Vertical Attenuation Coefficient			
Southeast Grand Banks	0.02		0.0001
Flemish Cap	0.001	0.0001	0.0001
Bonavista Bay	0.0001	ns	0.001
Seal Island		ns	
Euphotic Depth			
Southeast Grand Banks	0.001		0.0001
Flemish Cap	0.0001	0.0001	0.0001
Bonavista Bay	0.0001	ns	0.0001
Seal Island		0.01	

Table 3. *P*-values of inter-annual variations in abundance and biomass of seven dominant copepod species collected along the four oceanographic transects in the Newfoundland-Labrador region of DFO Southeast Grand Banks (SEGB); Flemish Cap (FC); Bonavista Bay (BB); and Seal Island (SI). P-values are estimated from the type III sums of squares from a generalized linear model that include year, season, and station identifier as categorical variables.

Abundance				
	SEGB	FC	BB	SI
Calanus finmarchicus	0.1201	0.0001	0.0106	0.0001
Calanus glacialis	0.2058	0.0152	0.0279	0.0005
Calanus hyperboreus	0.8430	0.0678	0.0370	0.0972
Calanoid nauplii	0.0001	0.0001	0.0760	0.0001
Metridia spp.	0.0403	0.0216	0.0016	0.0034
Oithona spp.	0.1757	0.0003	0.0385	0.0001
Pseudocalanus spp.	0.3755	0.0001	0.0884	0.0002

Biomass				
	SEGB	FC	BB	SI
Calanus finmarchicus	0.0320	0.0144	0.0094	0.0001
Calanus glacialis	0.1407	0.3210	0.0452	0.0142
Calanus hyperboreus	0.7728	0.0985	0.3089	0.3599
Calanoid nauplii	0.0001	0.0001	0.0760	0.0001
Metridia spp.	0.1403	0.0758	0.0027	0.5384
Oithona spp.	0.1757	0.0003	0.0385	0.0001
Pseudocalanus spp.	0.5481	0.0001	0.0188	0.0016

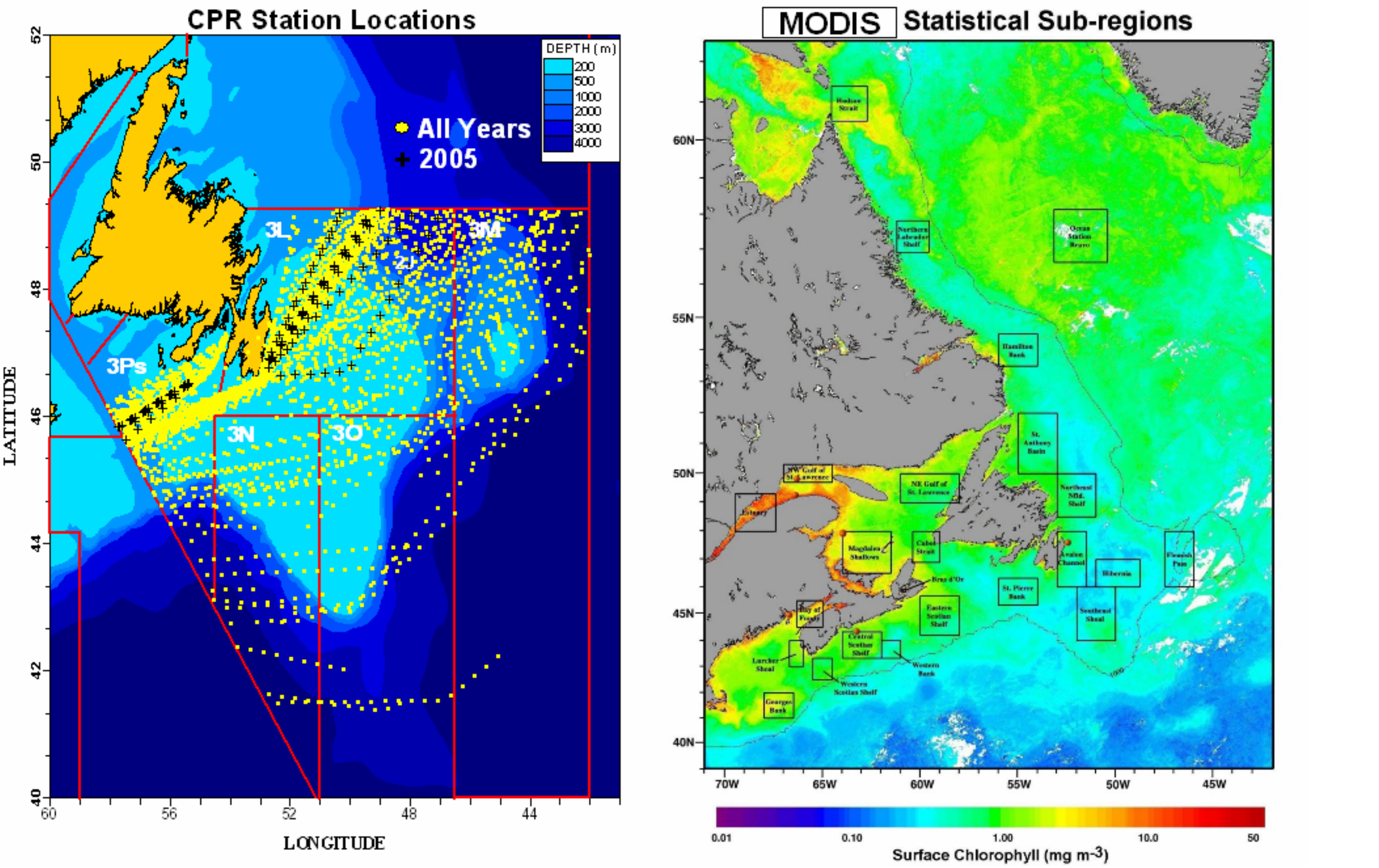


Figure 1. Station location for the continuous plankton recorder during 1961-2005, and statistical sub-regions in the Northwest Atlantic for analysis of surface chlorophyll *a* from MODIS ocean colour imagery.

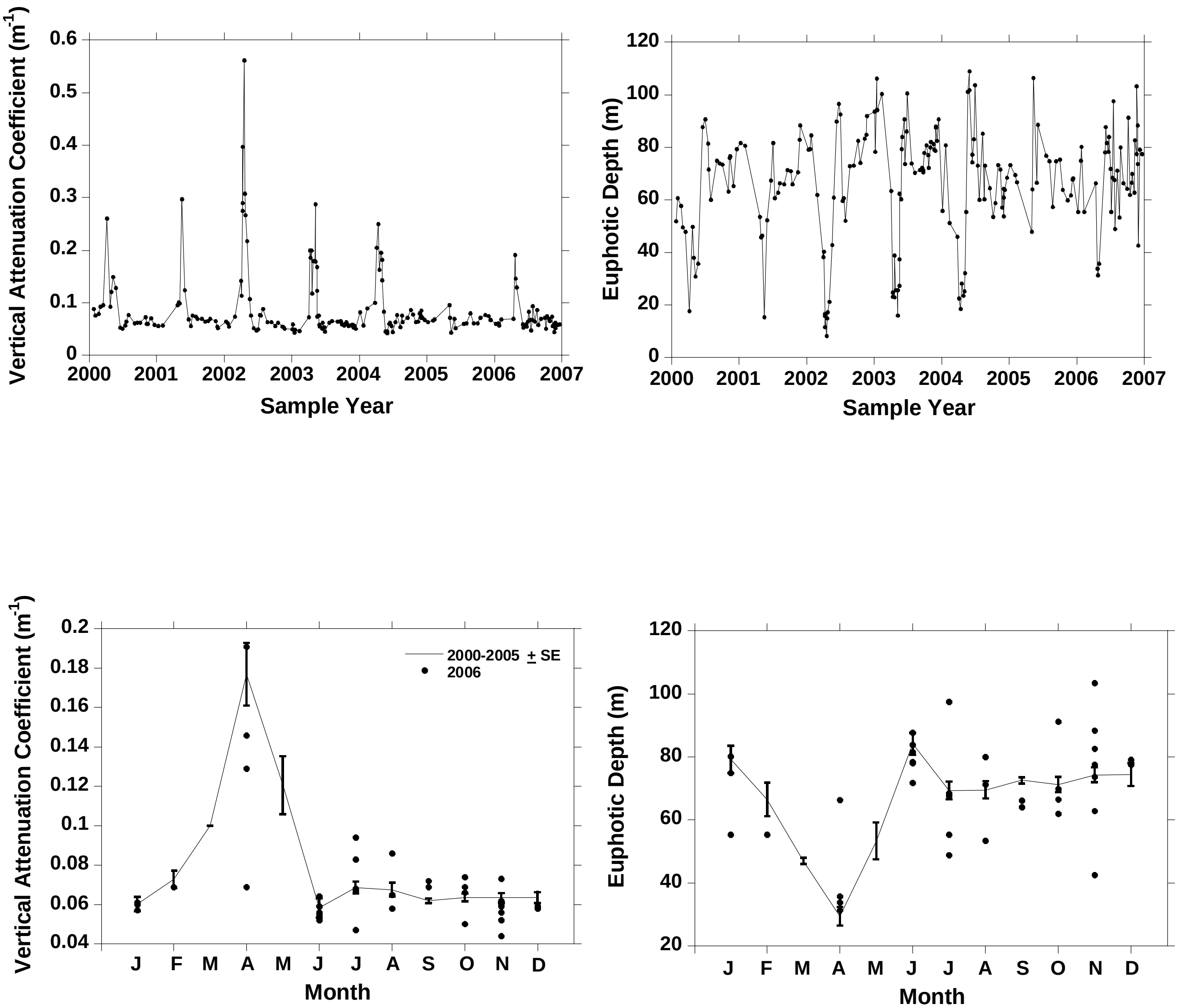


Figure 2. Optical properties showing time series of the vertical attenuation coefficient and euphotic depth (depth of the 1 % light) at Station 27 (upper panels), compared with the seasonal cycle from 2000-05 and 2006 data (lower panels).

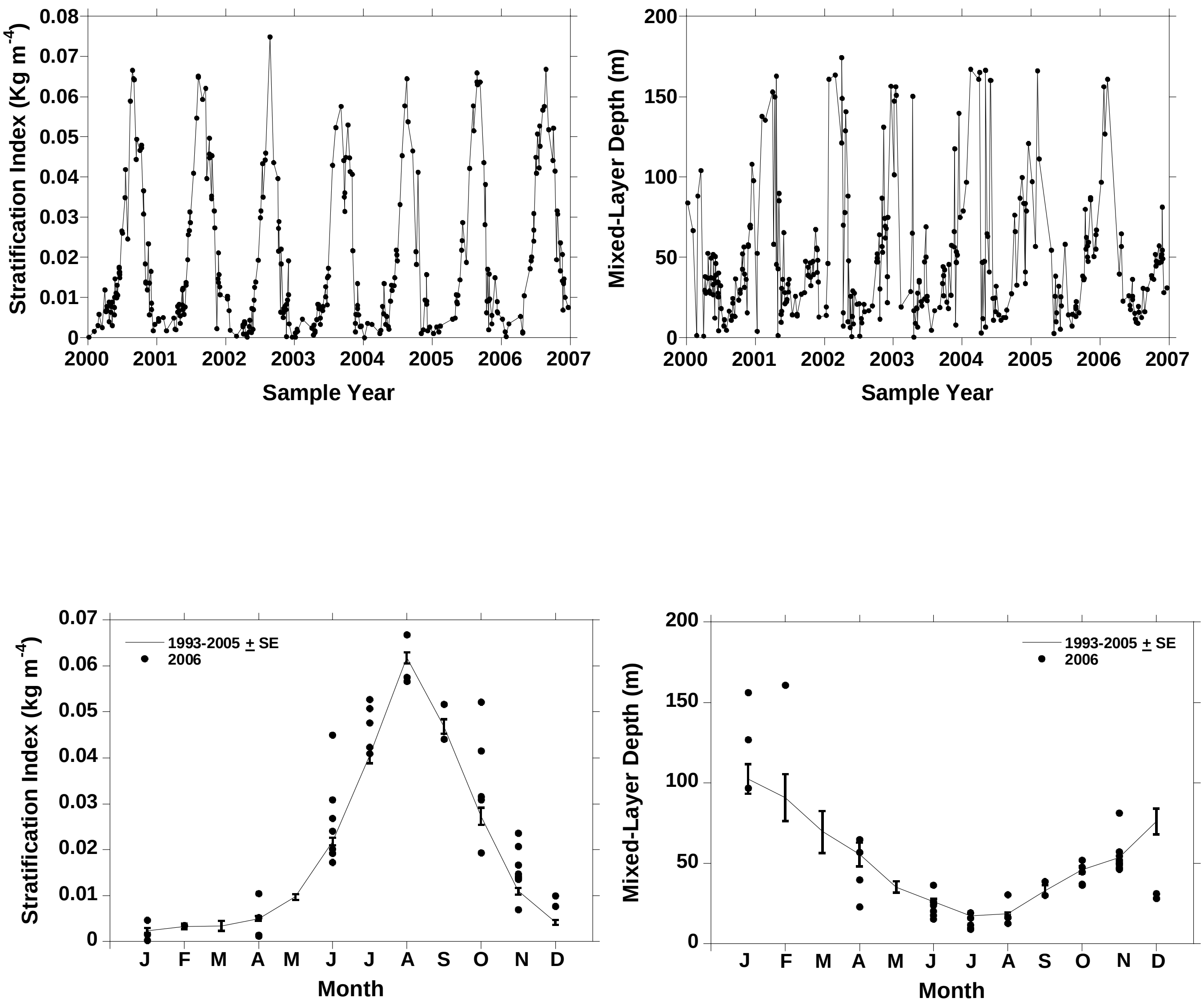


Figure 3. Mixing properties showing time series of the stratification index and mixed-layer depth at Station 27 (upper panels), compared with the seasonal cycle during 1993-2005 and 2006 data (lower panels).

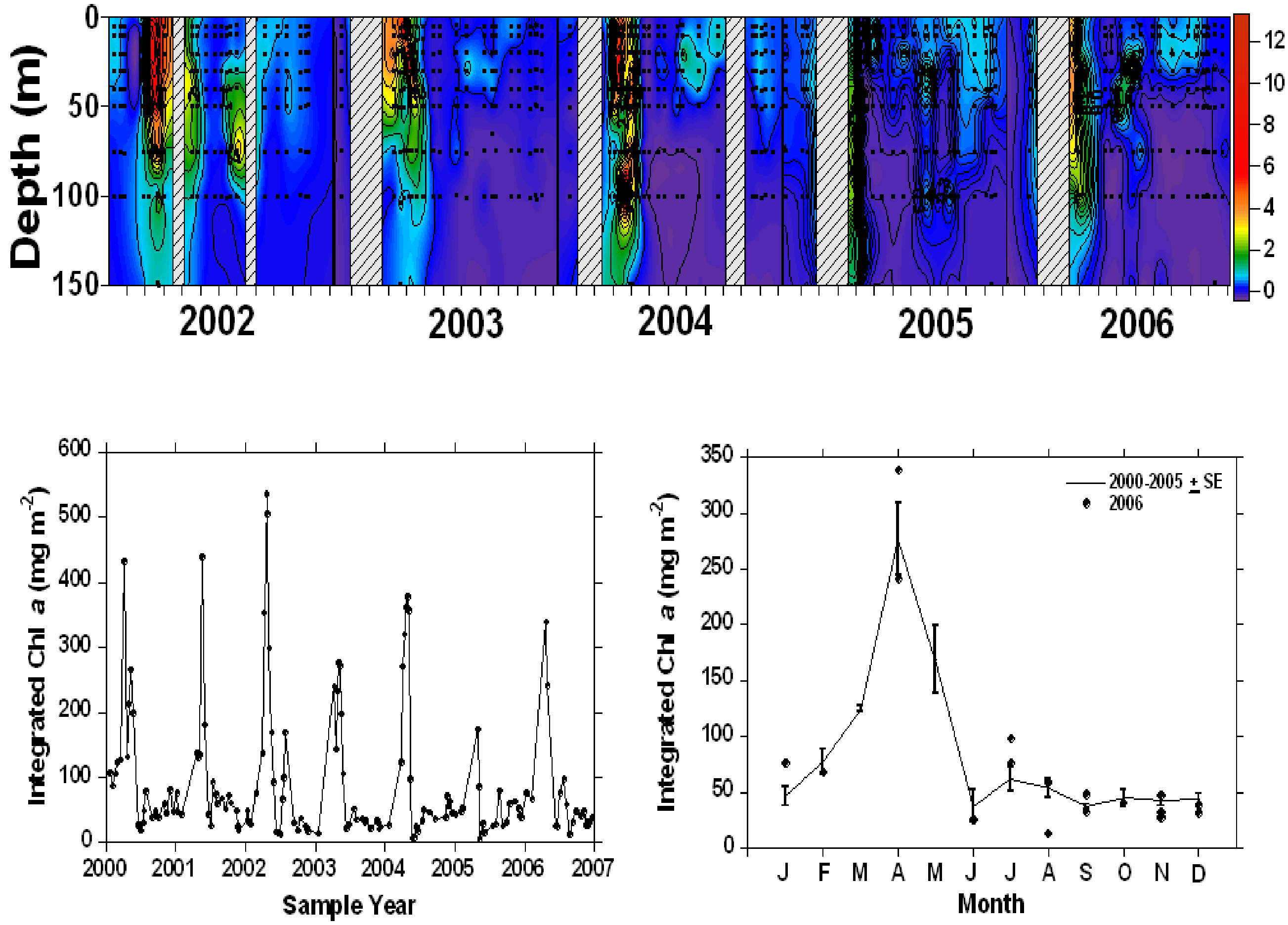


Figure 4. Time series of vertical chlorophyll *a* structure (upper panel), inventories (surface–100 m integrals; lower left panel), and seasonal cycle (lower right panel) from 2000-05 and 2006 data at Station 27.

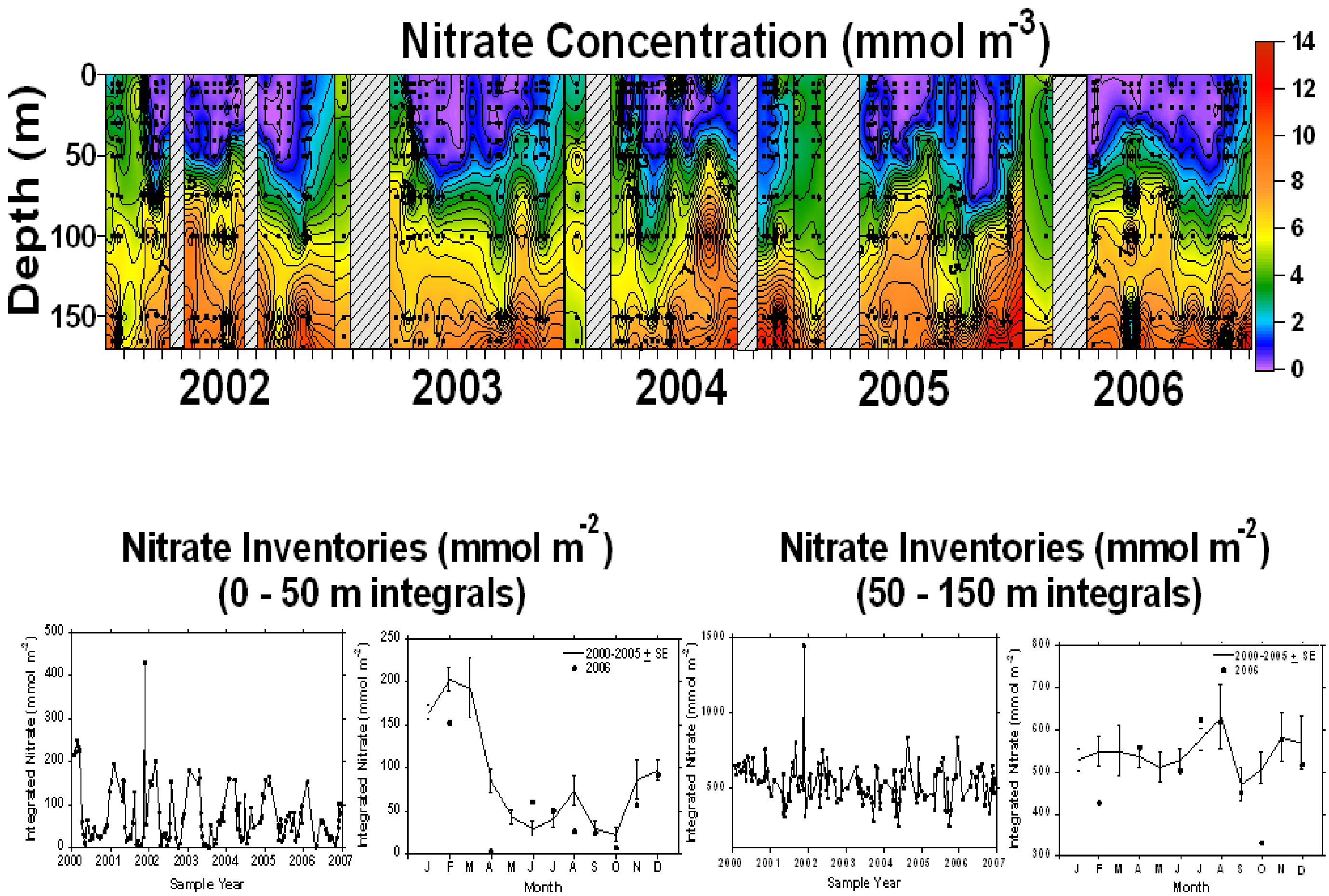


Figure 5. Time series of vertical nitrate structure (upper panel), shallow nitrate inventories (surface–50 m integrals; lower panels), and corresponding seasonal cycles from 2000-05 and 2006 data at Station 27.

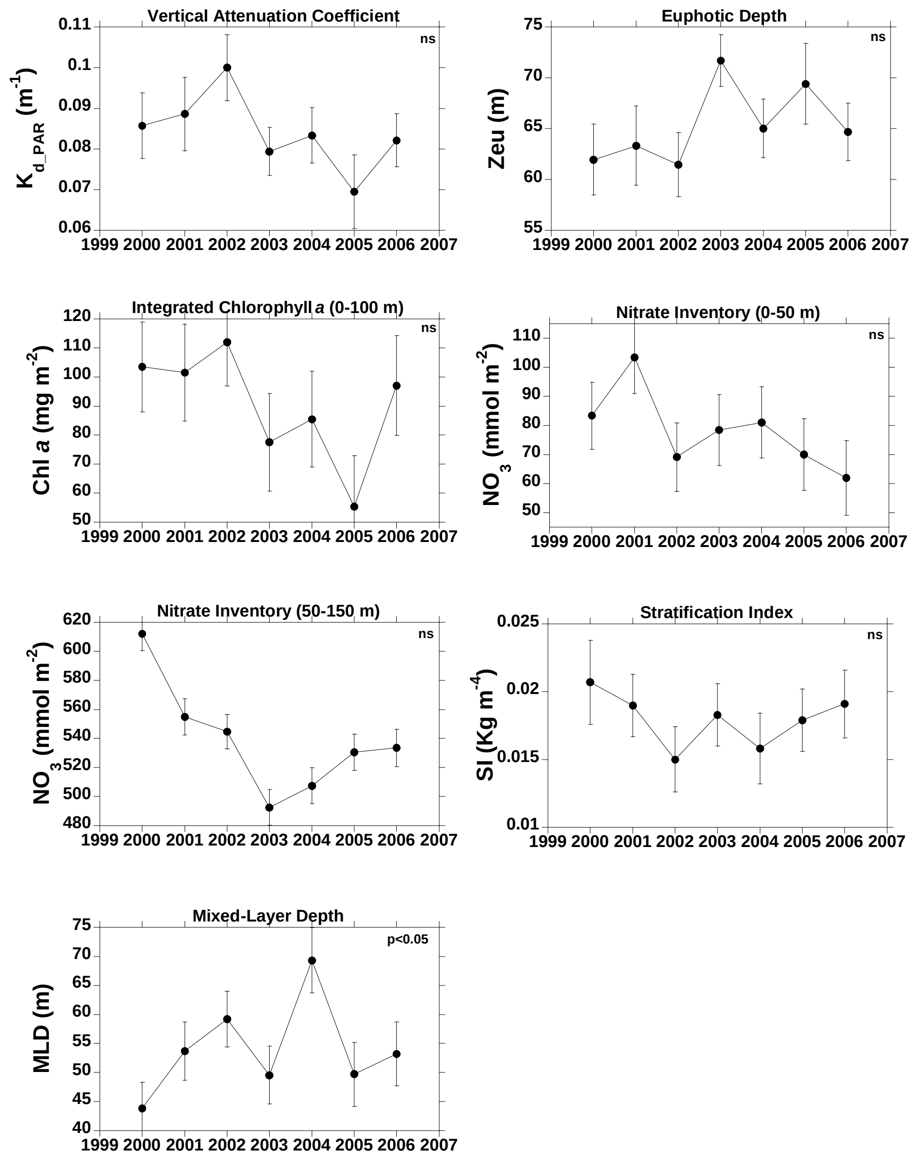


Figure 6. Seasonally-adjusted annual mean estimates (± standard error) of the various optical, chemical, and physical properties for Station 27 during 2000-06. Significance levels of the overall year effect are in the upper right-hand corner.

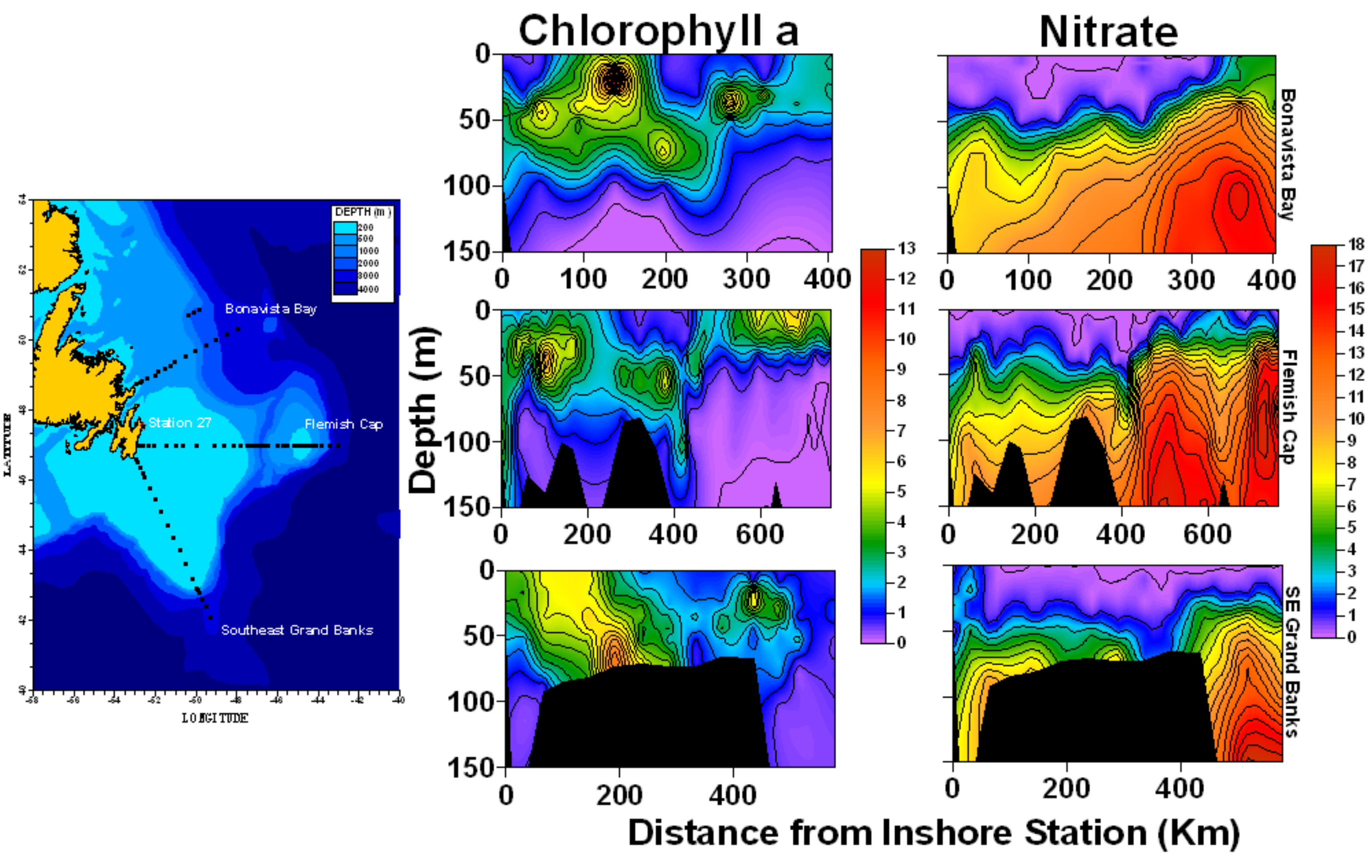


Figure 7. Vertical nitrate and chlorophyll *a* structure along the Newfoundland Shelf sections during the spring survey in 2006.

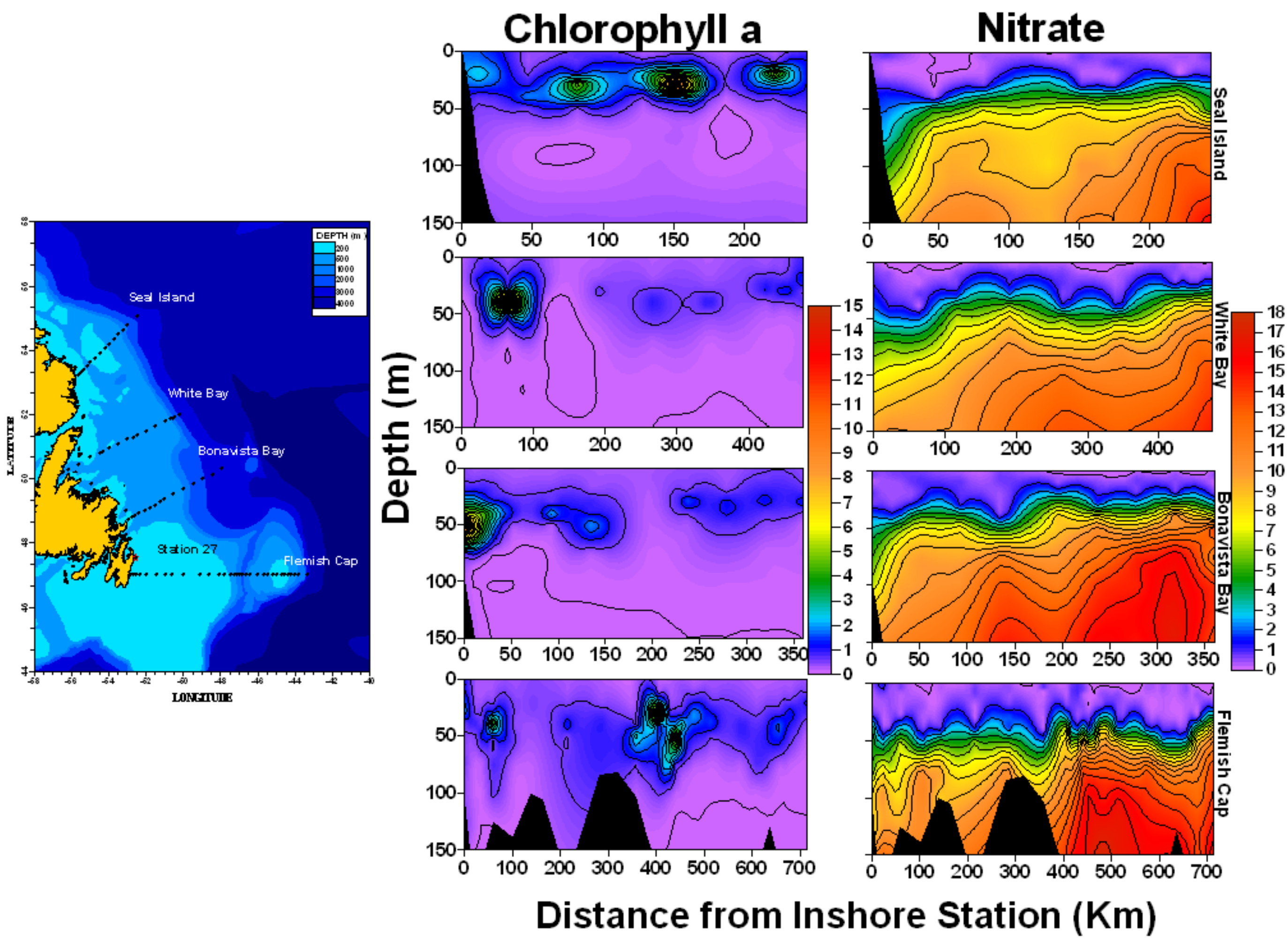


Figure 8. Vertical nitrate and chlorophyll a structure along the Newfoundland and Labrador Shelf sections during the summer survey in 2006.

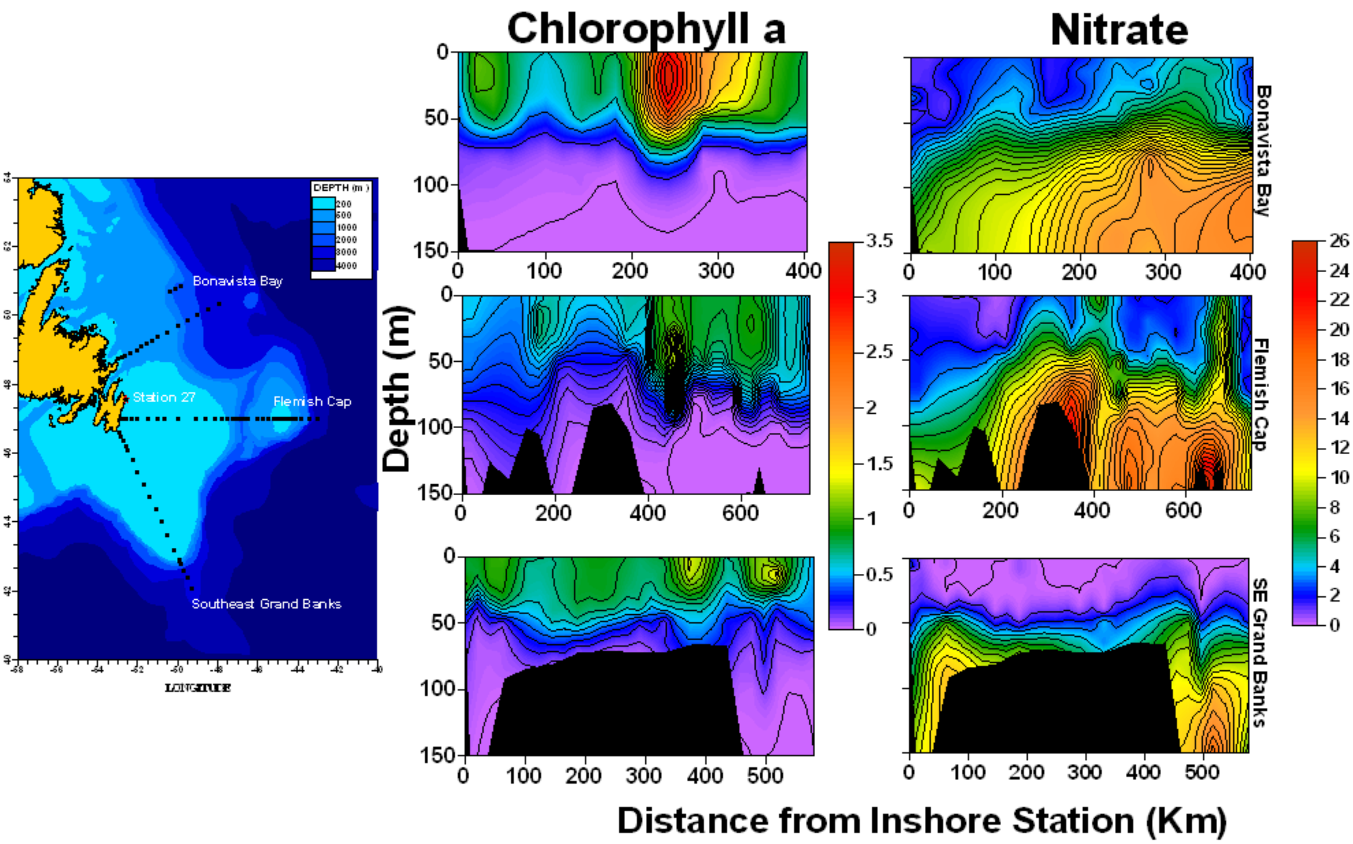


Figure 9. Vertical nitrate and chlorophyll *a* structure along the Newfoundland Shelf sections during the autumn survey in 2006.

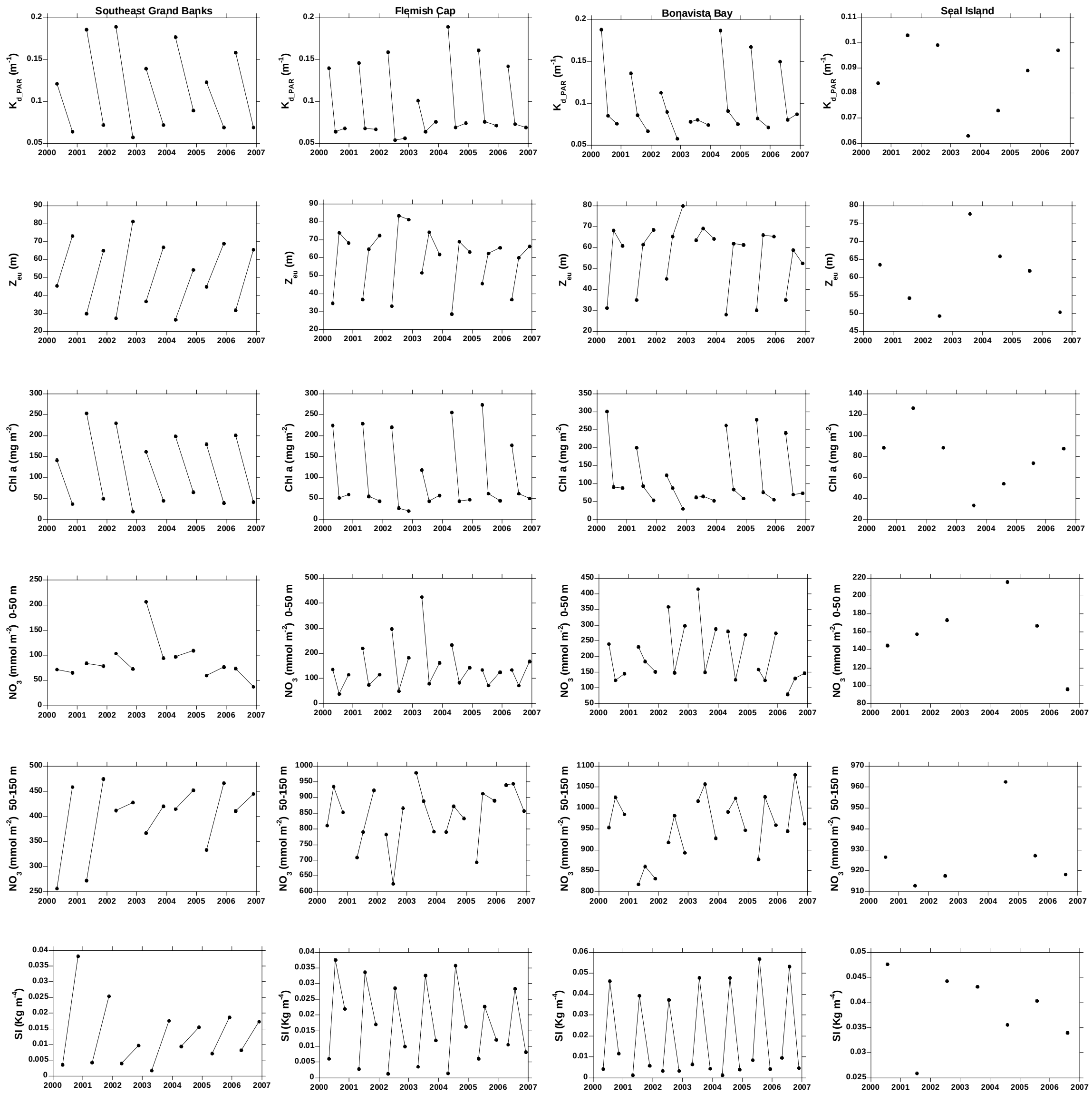


Figure 10. Seasonal mean vertical attenuation coefficient (K_{d_PAR}), euphotic depth (Z_{eu}), integrated chlorophyll (0-100 m), nitrate inventories (0-50 m and 50-150 m), and stratification index for the four oceanographic transects. Seasonal transect means are based on the results of a generalized linear model that includes year and station identifier as categorical variables. Note that the Southern Grand Banks transect is only surveyed in the spring and fall and the Seal Island transect is only surveyed during the summer. Flemish Cap and Bonavista Bay transects are surveyed in the spring, summer and fall.

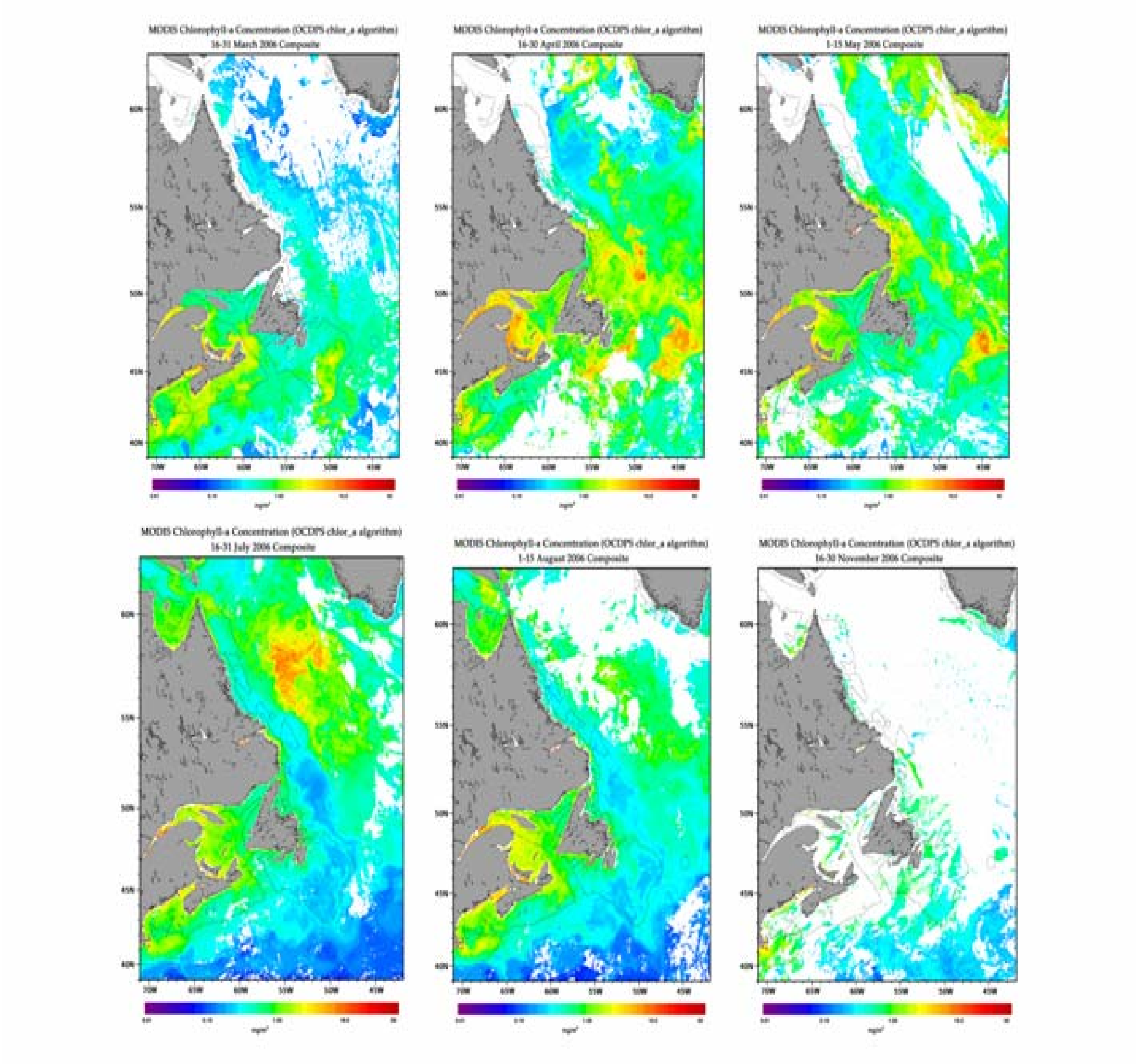


Figure 11. MODIS bi-weekly composite images of surface chlorophyll *a* concentrations in the NW Atlantic region during AZMP seasonal surveys in 2006.

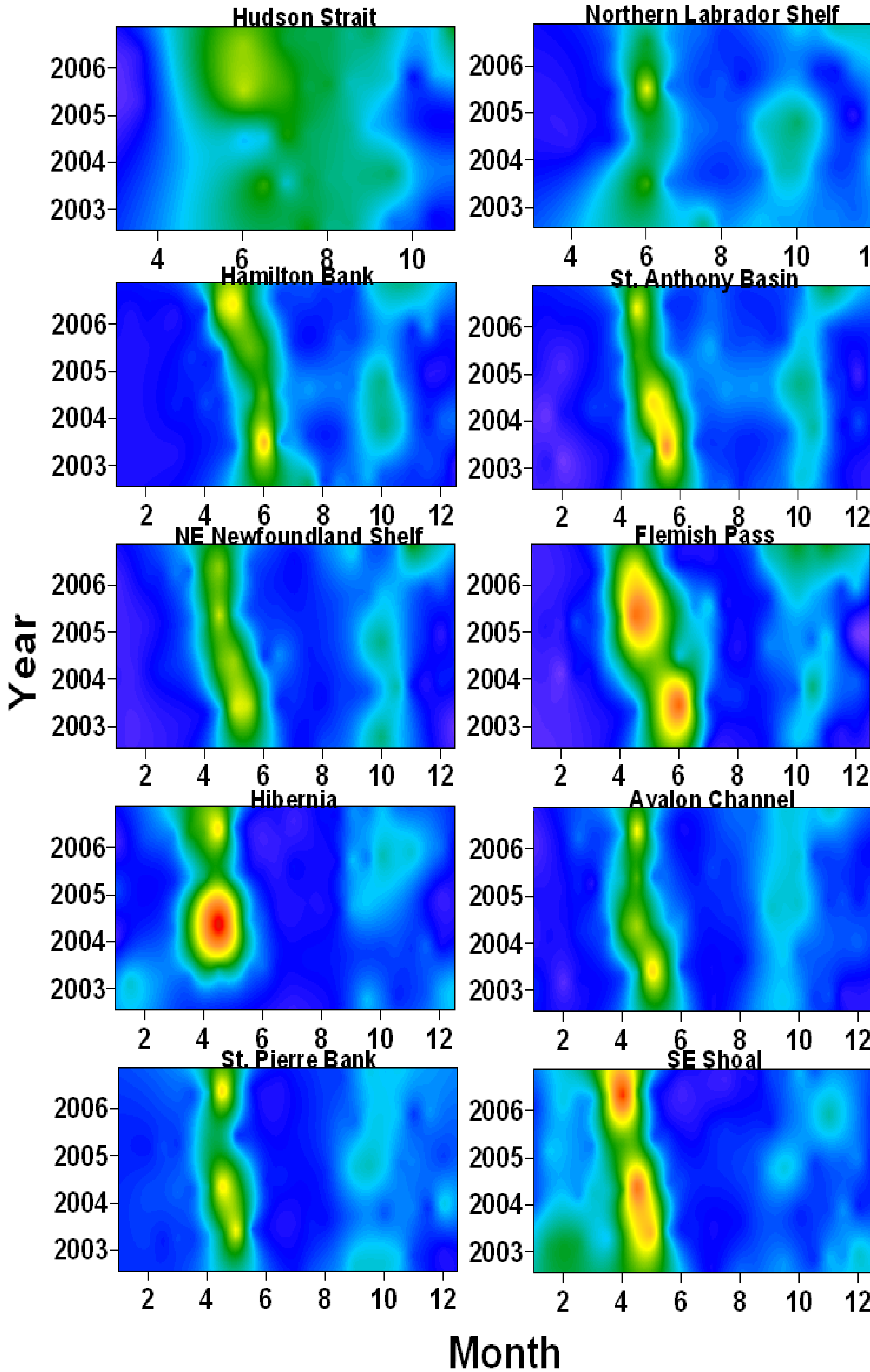


Figure 12. Time series of mean surface chlorophyll *a* concentrations from MODIS bi-weekly ocean colour composites for statistical sub-regions in the Newfoundland and Labrador region during 2002-2006. See Figure xx for locations of statistical sub-regions.

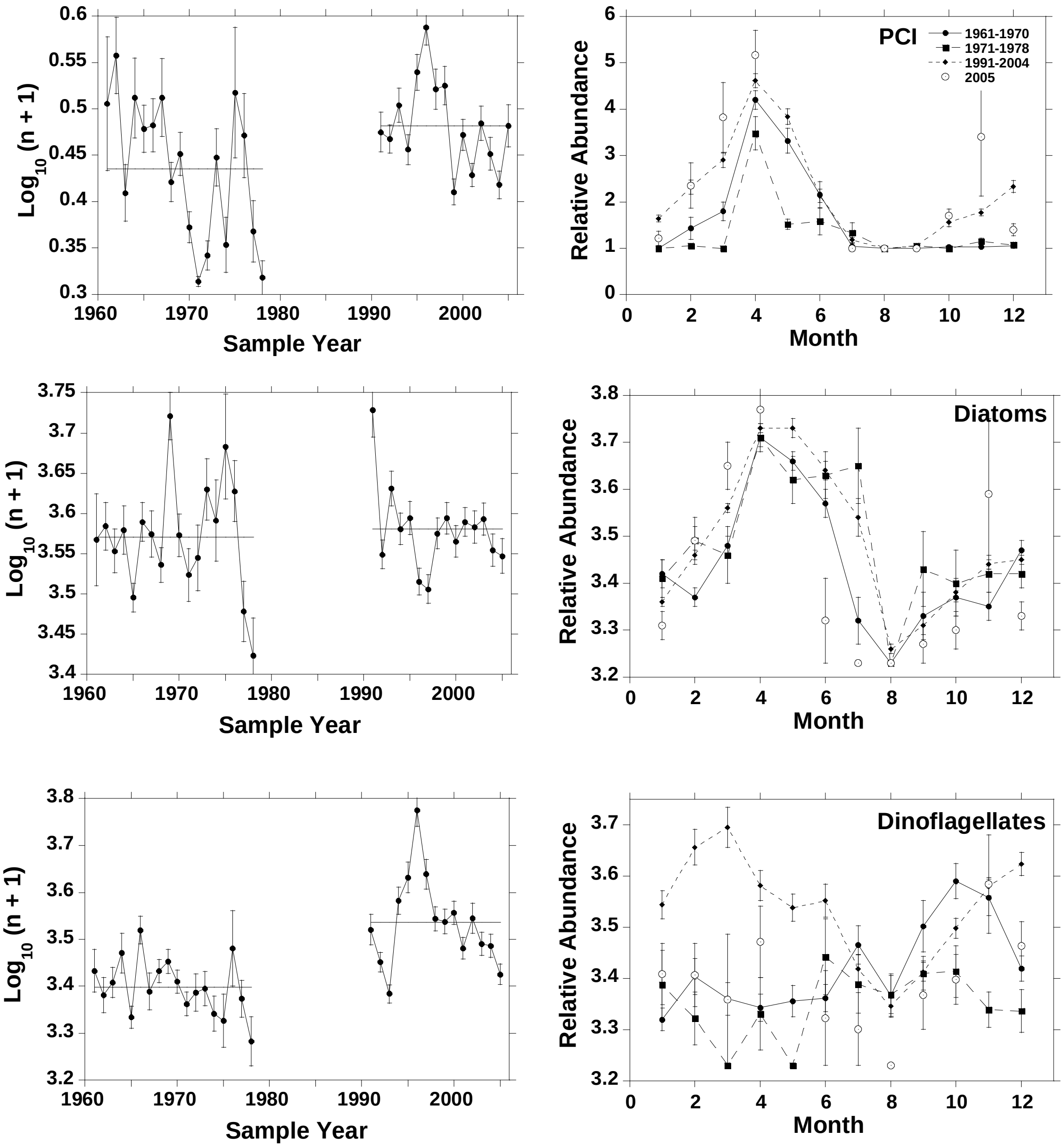


Figure 13. Time series of relative phytoplankton biomass (phytoplankton colour index – PCI), and diatom and dinoflagellate relative annual abundances and corresponding seasonal cycle on the Grand Banks and northeast Newfoundland Shelf (NAFO Division 3LMNOPs) from CPR surveys during 1961-2005. Monthly means for the 1960s, 1970s, 1991-2004, and most recent year shown for comparison. Vertical bars are standard errors.

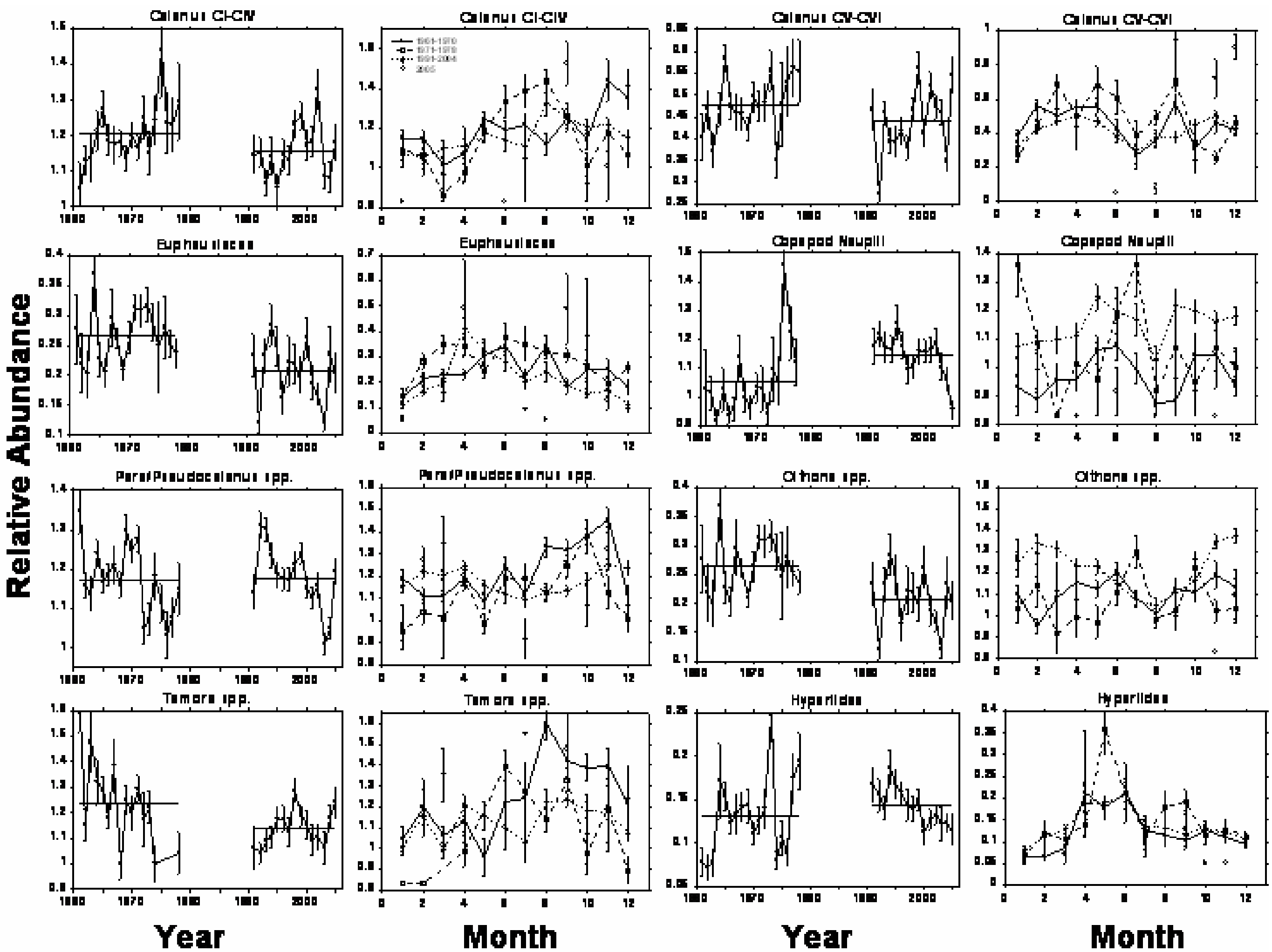


Figure 14. Time series of relative annual abundances of selected zooplankton species and corresponding seasonal cycle on the Grand Banks and northeast Newfoundland Shelf (NAFO Division 3LMNOPs) from CPR surveys during 1961-2005. Monthly means for the 1960s, 1970s, 1991-2004, and most recent year shown for comparison. Vertical bars are standard errors.

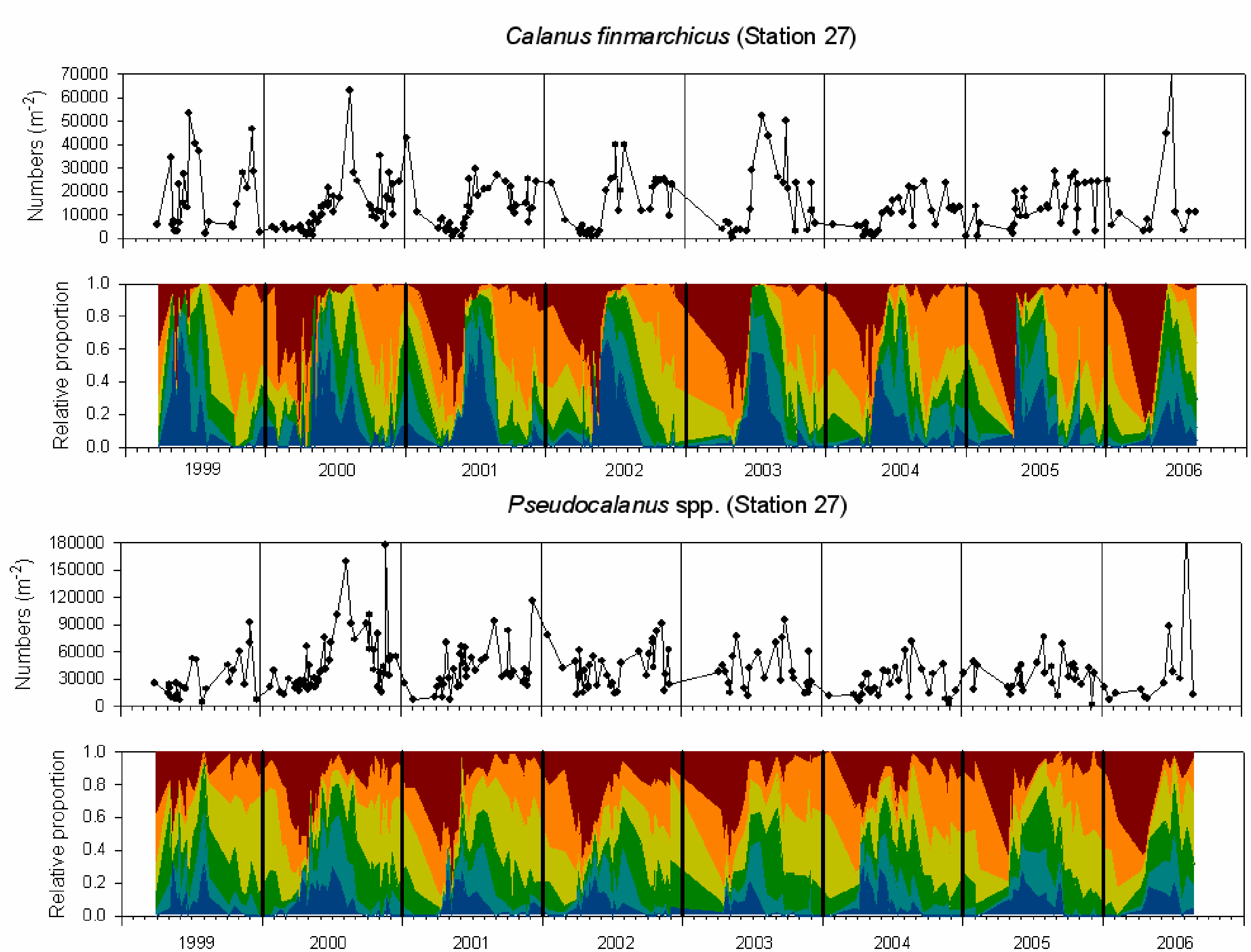


Figure 15. Seasonal cycle of abundance and stage distribution of *Calanus finmarchicus* and *Pseudocalanus* spp. at Station 27 for the period 1999-2006. (Stage CI (blue), CII (teal), CIII (green), CIV (yellow), CV (orange), CVI (brown)).

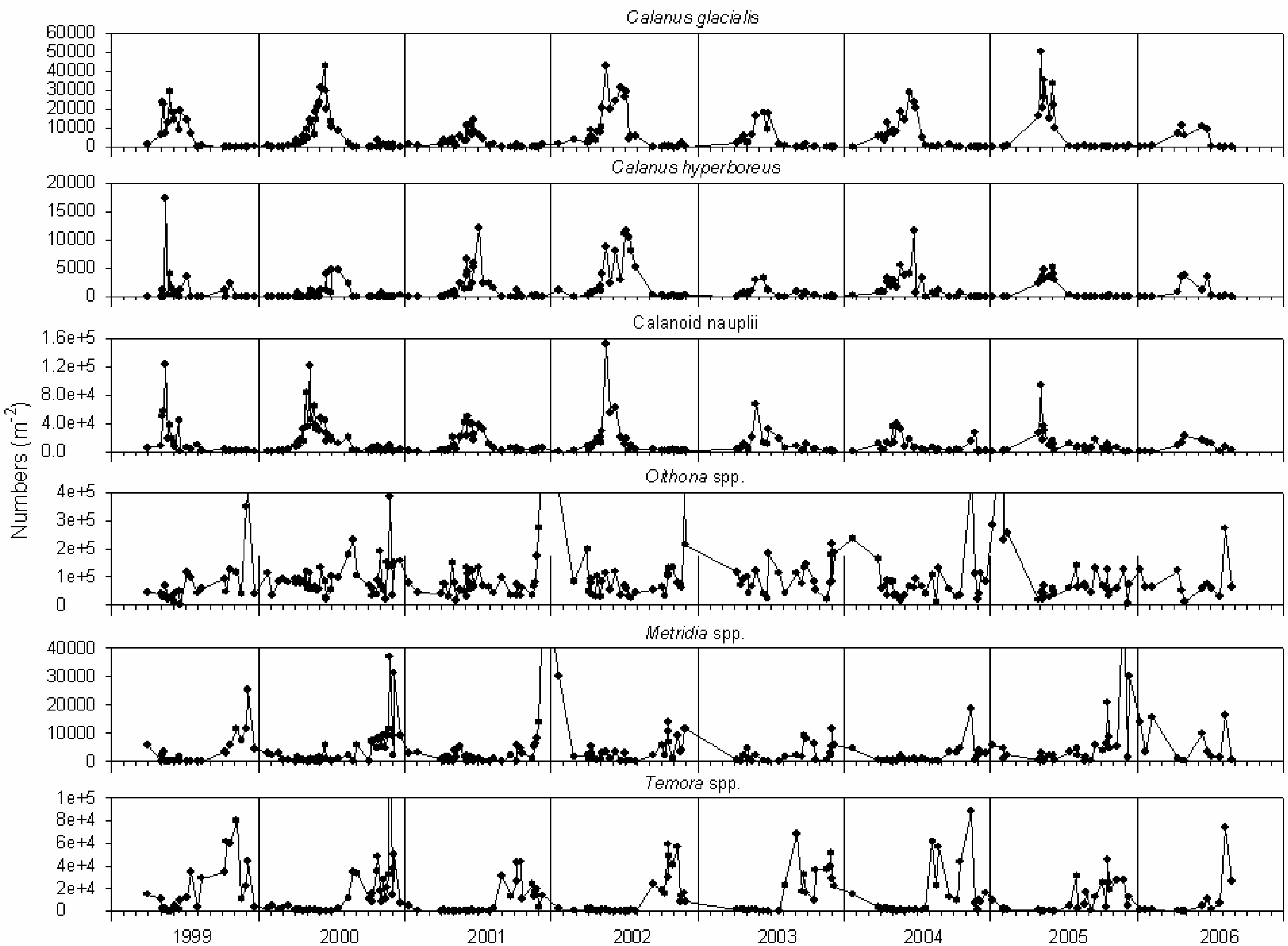
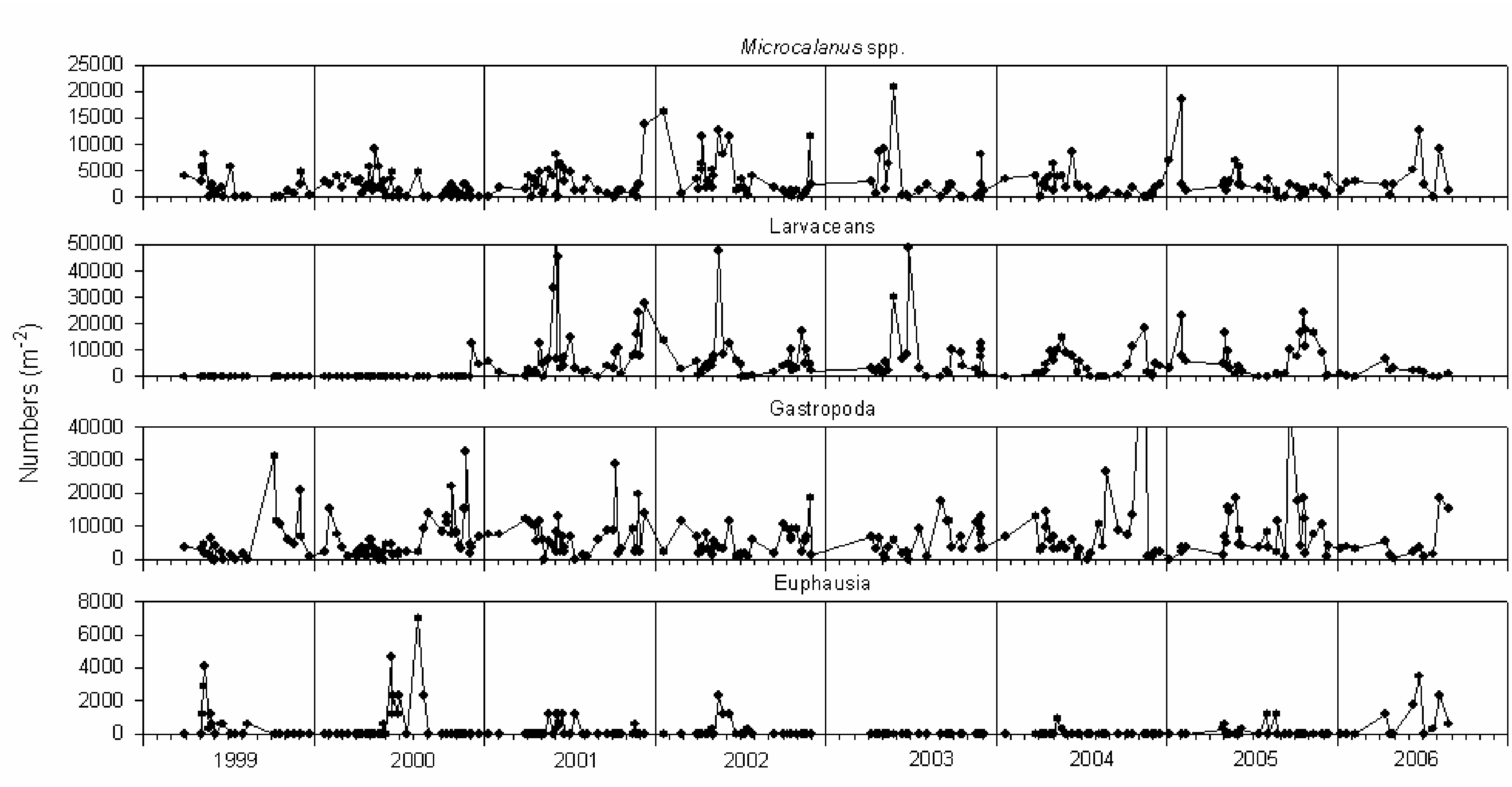


Figure 16. Seasonal cycle of abundance of ten dominant zooplankton taxa from Station 27 for the period 1999-2006.

Figure 16 (Cont'd.)



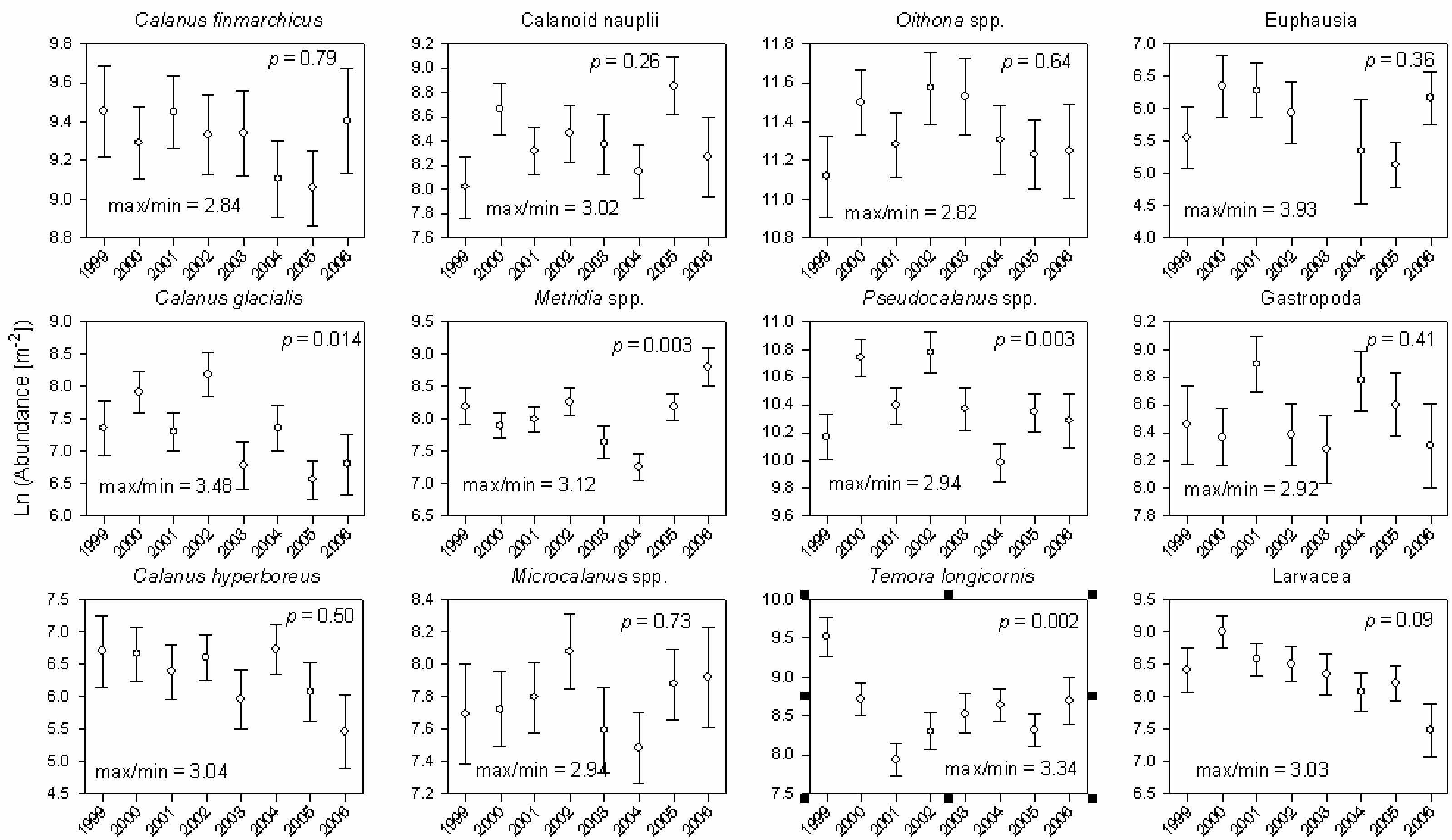


Figure 17. Seasonally-adjusted estimate of the mean abundance of twelve dominant zooplankton taxa from Station 27 for the period 1999-2006. The error bars represent standard errors. The *p*-value in the upper right hand corner indicates the probability of significant inter-annual variations in abundance based on type III sums of squares. The maximum-to-minimum ratio in the lower left hand corner indicates the magnitude of the variation in abundance during the six year period.

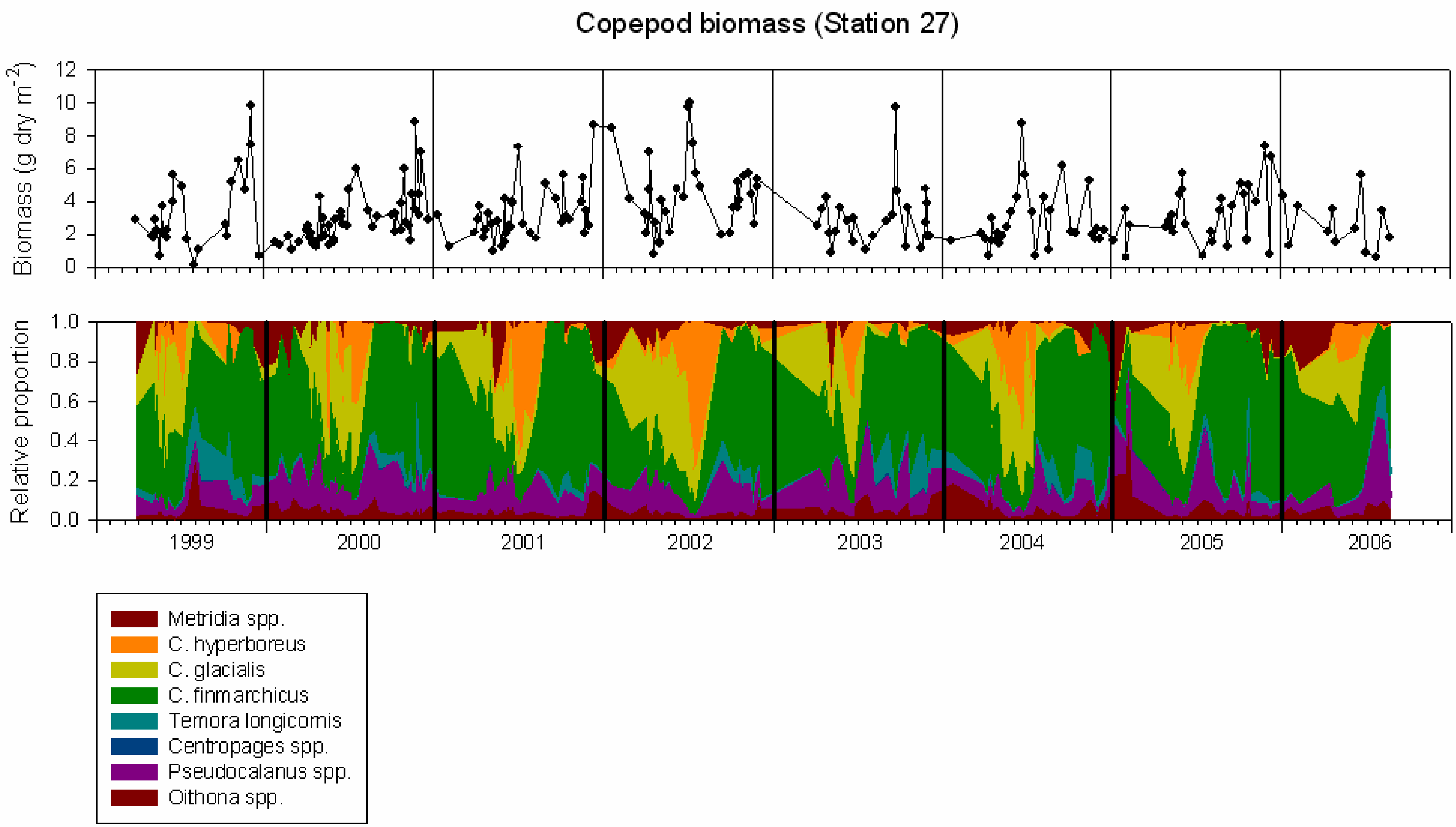


Figure 18. Seasonal cycle of total biomass and species distribution of the dominant copepods at Station 27 for the period 1999-2006.

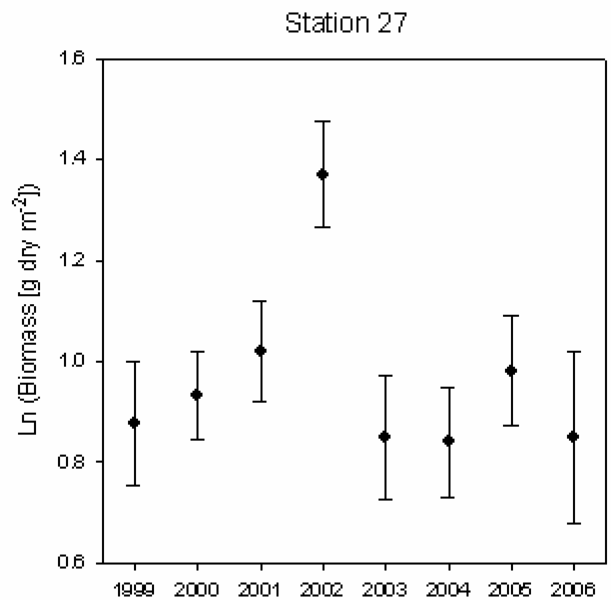


Figure 19. Seasonally-adjusted estimates of the mean biomass of 8 dominant copepod species from Station 27 for the period 1999-2006. The error bars represent standard errors.

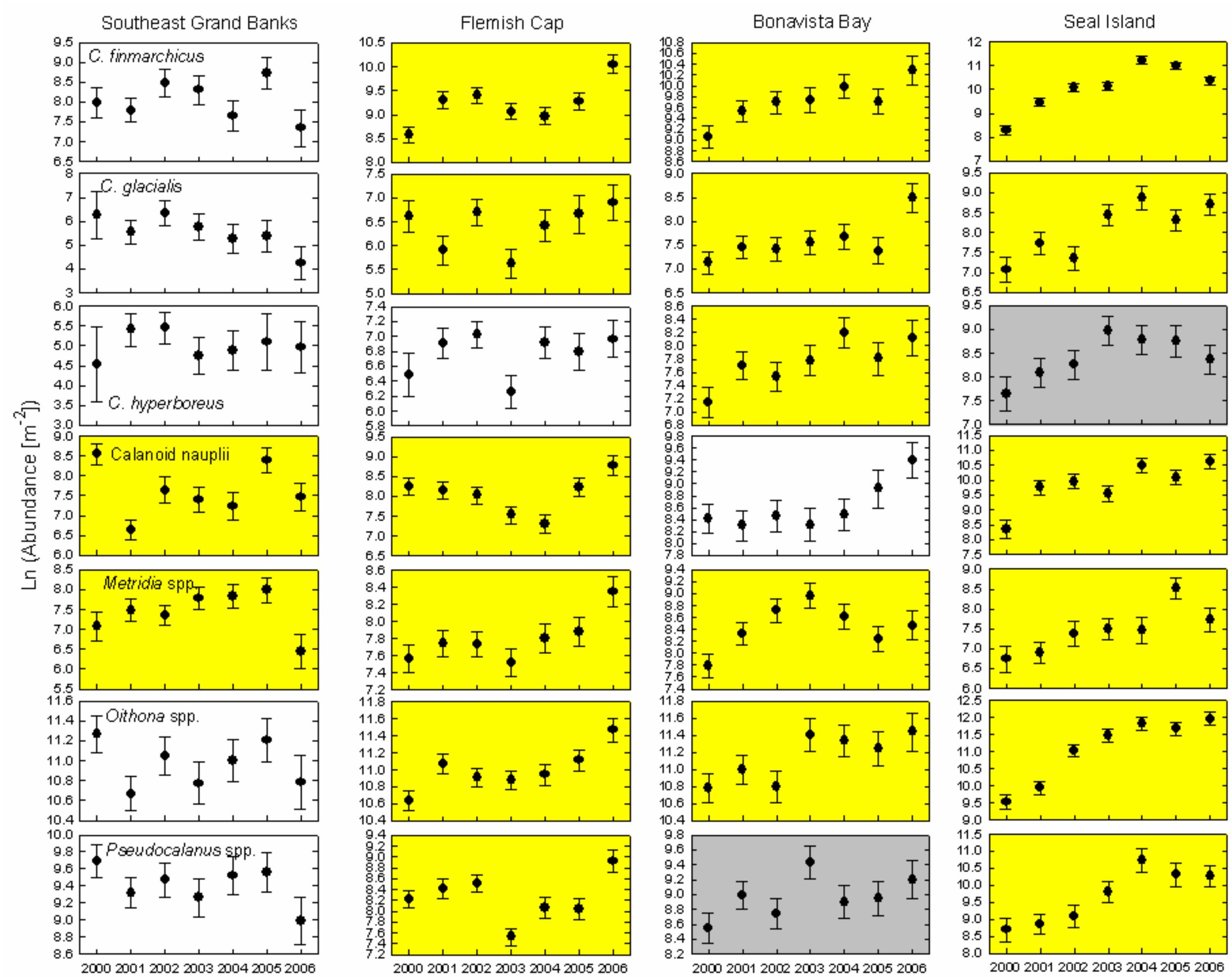


Figure 20. Seasonally-adjusted estimate of the mean abundance of seven dominant copepod taxa from the oceanographic transects for the period 2000-06. The error bars represent standard errors. Values from the Southeast Grand Banks are based on two occupations per year (spring, fall); values from the Flemish Cap and Bonavista transects are based on three occupations per year (spring, summer, fall); values from the Seal Island transect are based on one occupation per year (summer). Yellow backgrounds indicate significant inter-annual differences in abundance. Grey Backgrounds indicate that variations in abundance were significant in 2005 but not in 2006.

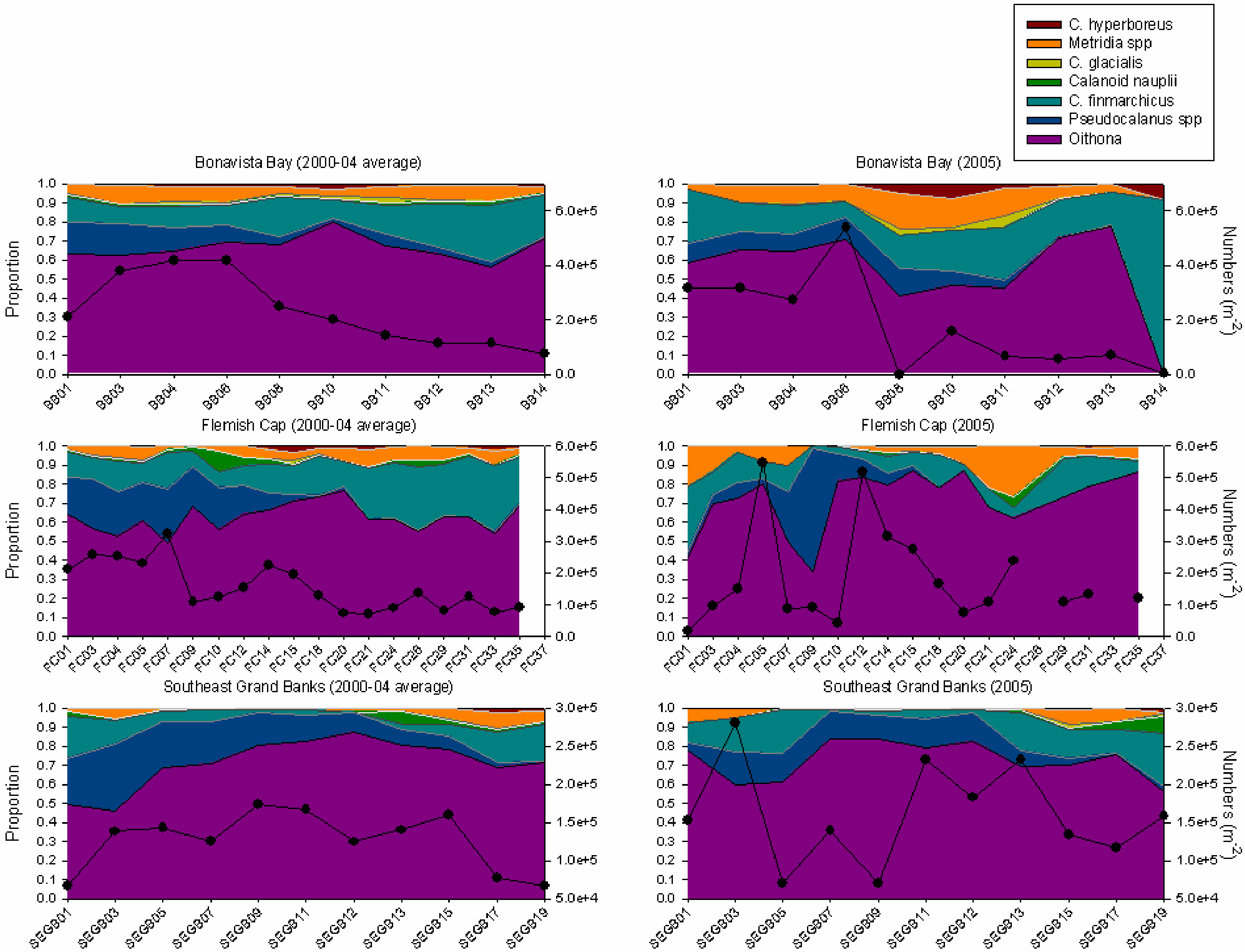
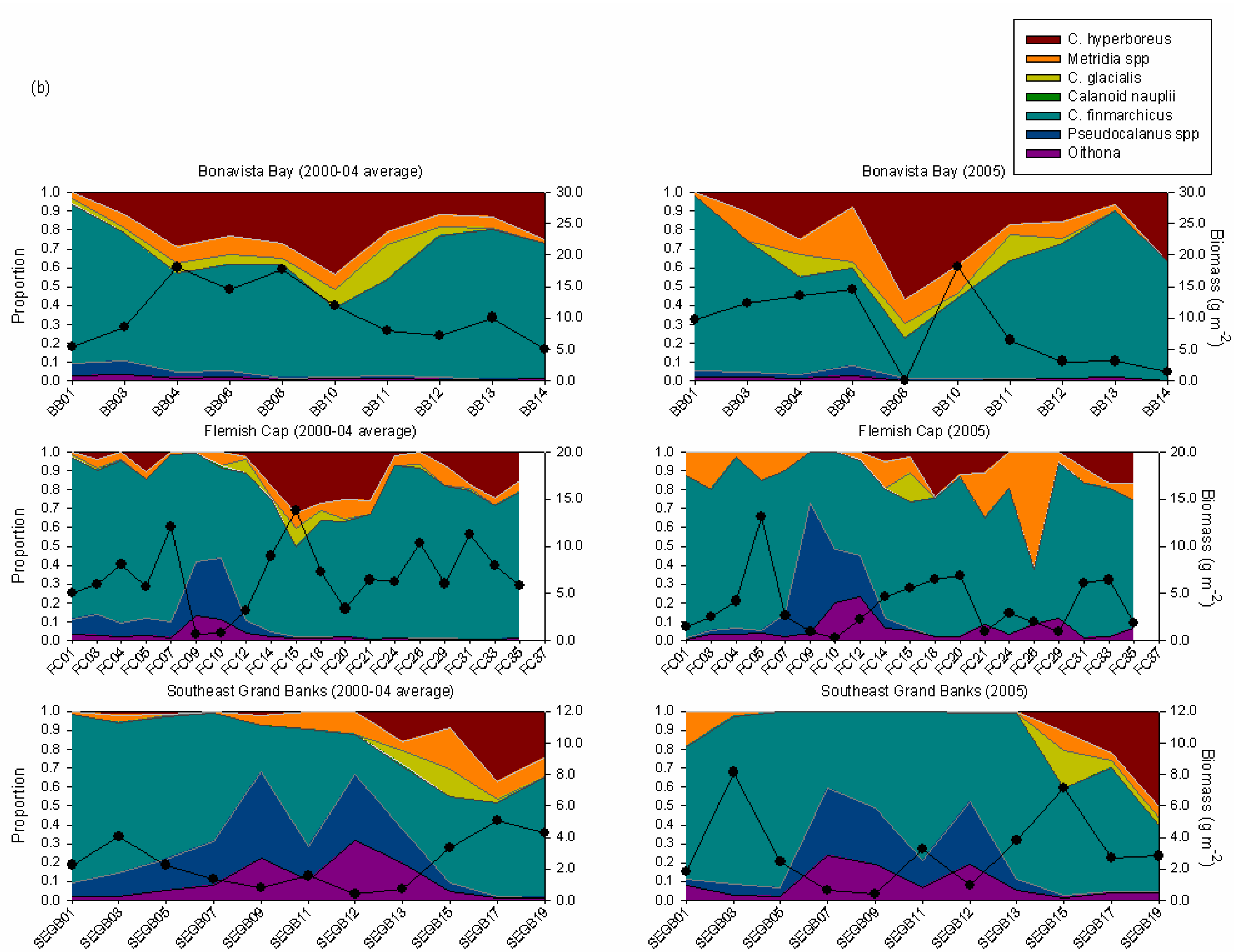


Figure 21. Spatial distribution in (a) abundance, (b) biomass, and species composition for the seven dominant copepod taxa collected along oceanographic transects sampled in the fall surveys. The left-hand panels show the average distribution for 2000-04 while the right-hand panels shows the observations for 2005.

Figure 21 (Cont'd.)



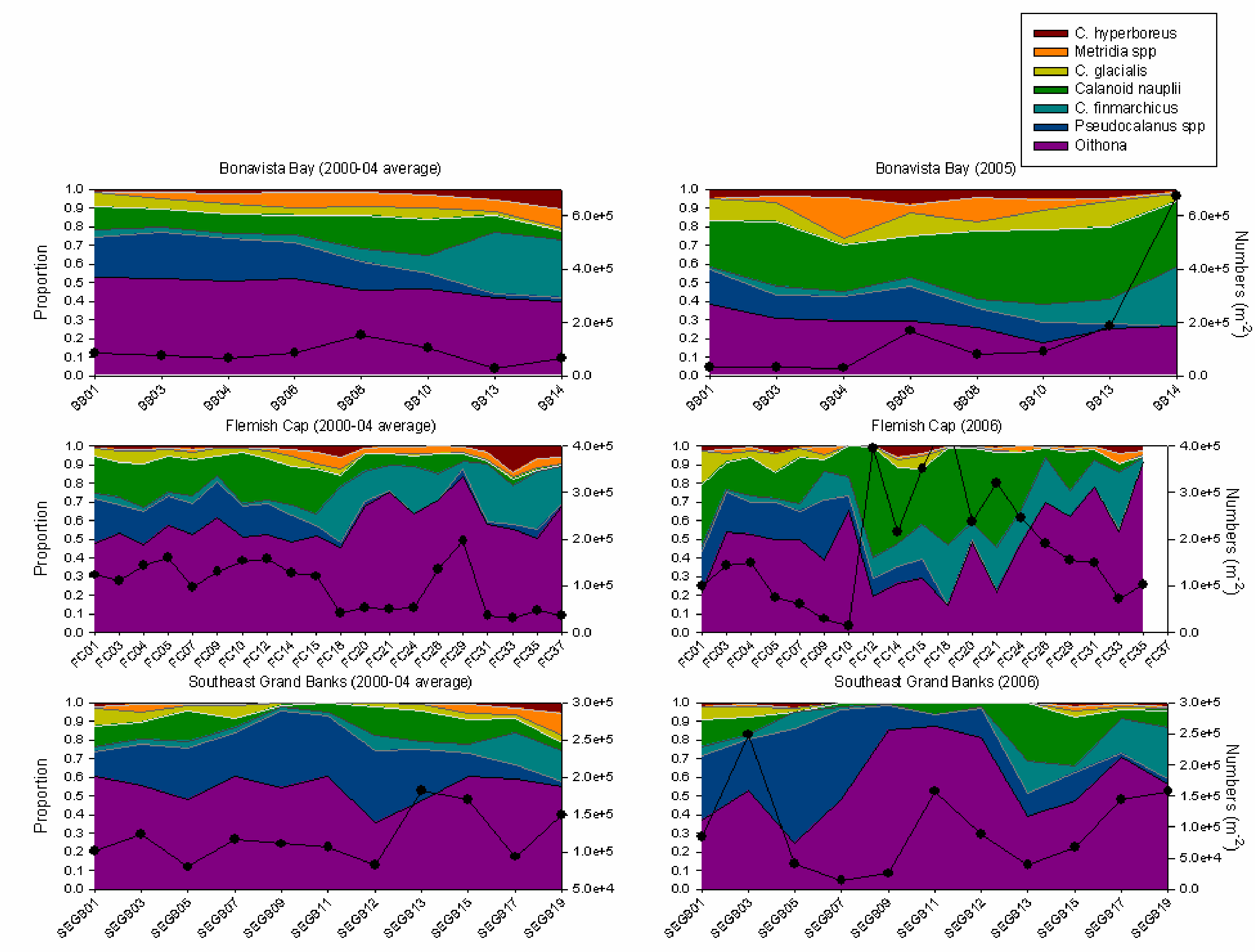
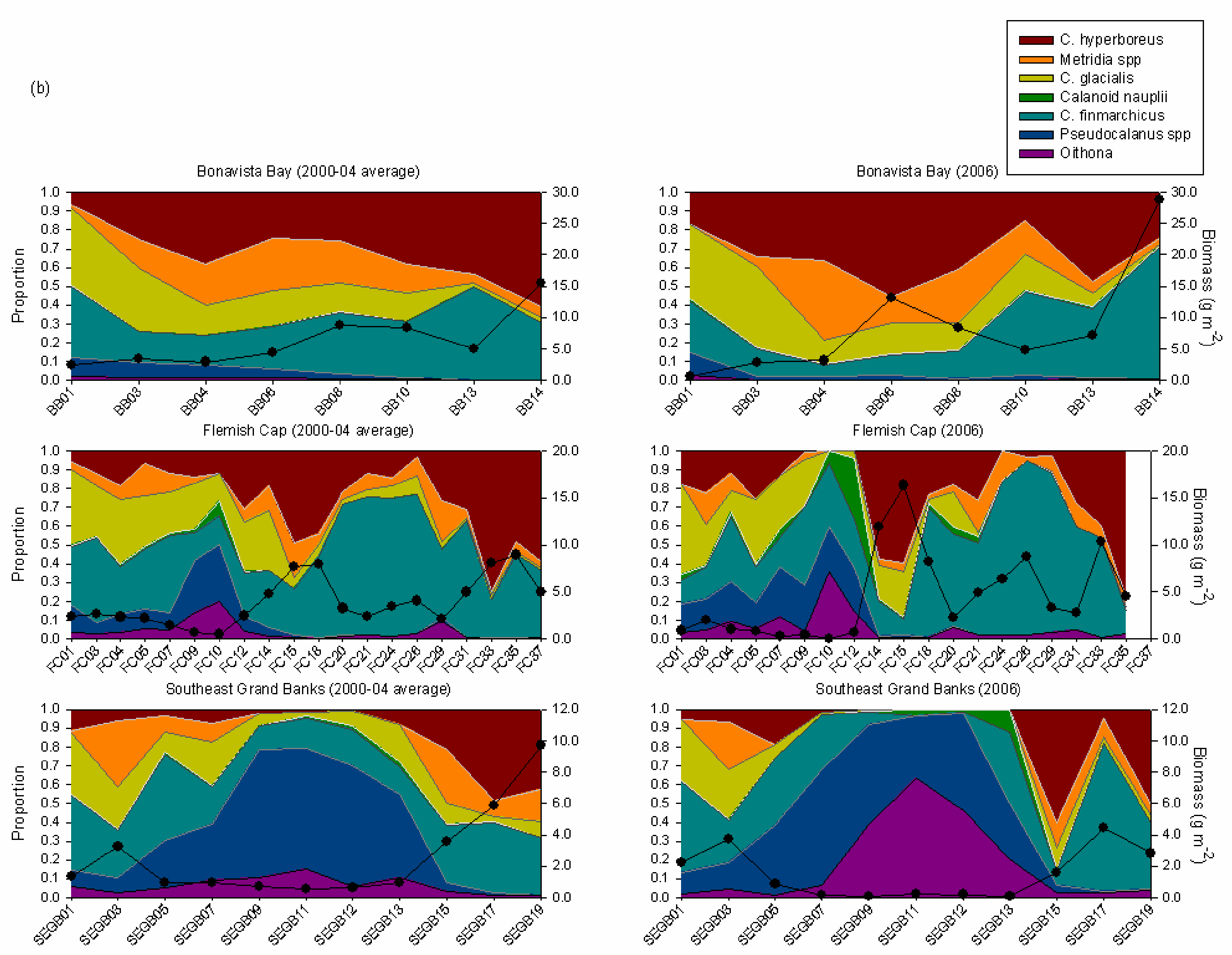


Figure 22. Spatial distribution in (a) abundance, (b) biomass, and species composition for the seven dominant copepod taxa collected along oceanographic transects sampled in the spring surveys. The left-hand panels show the average distribution for 2000-04 while the right-hand panels shows the observations for 2006.

Figure 22 (Cont'd.)



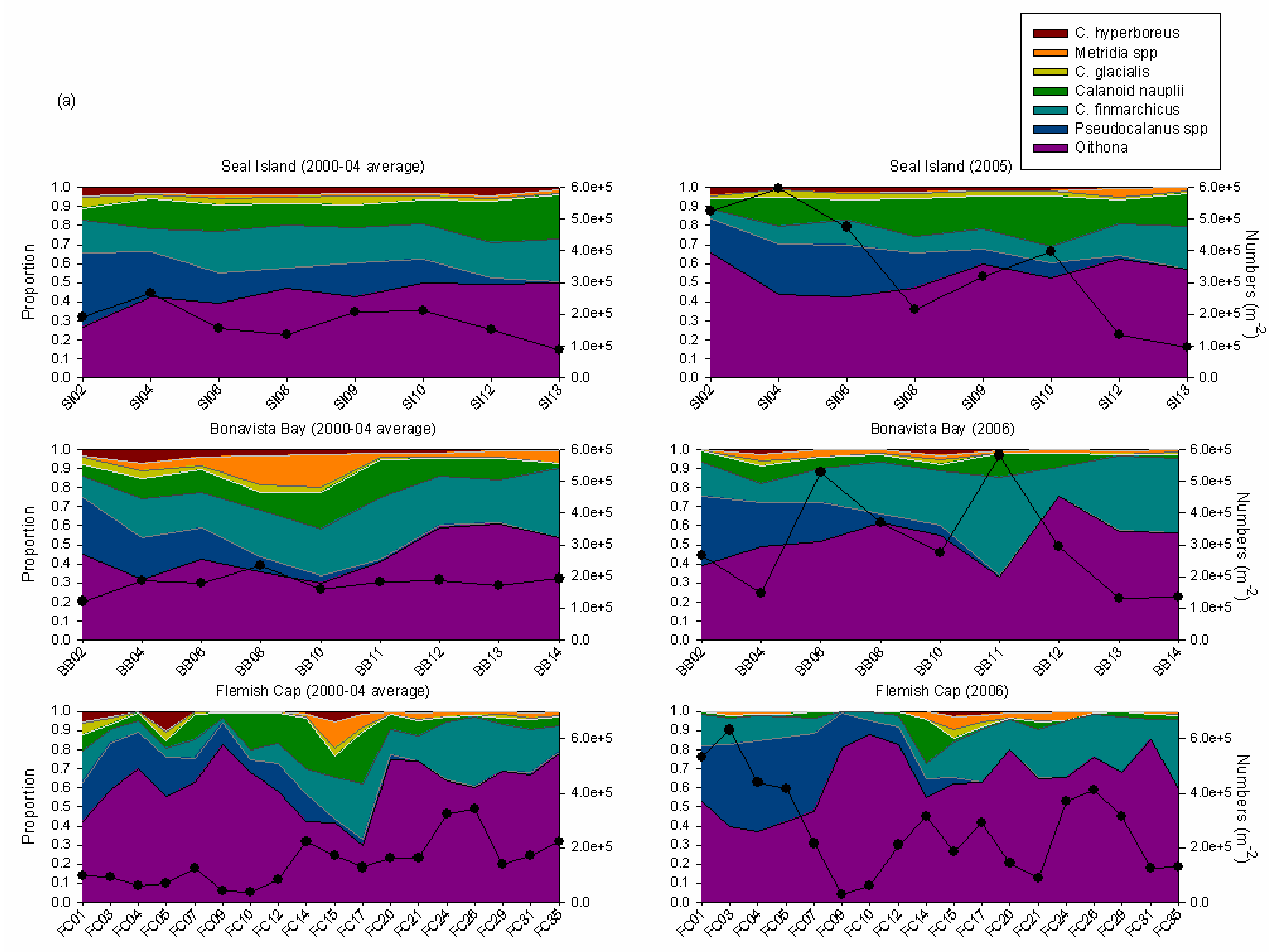
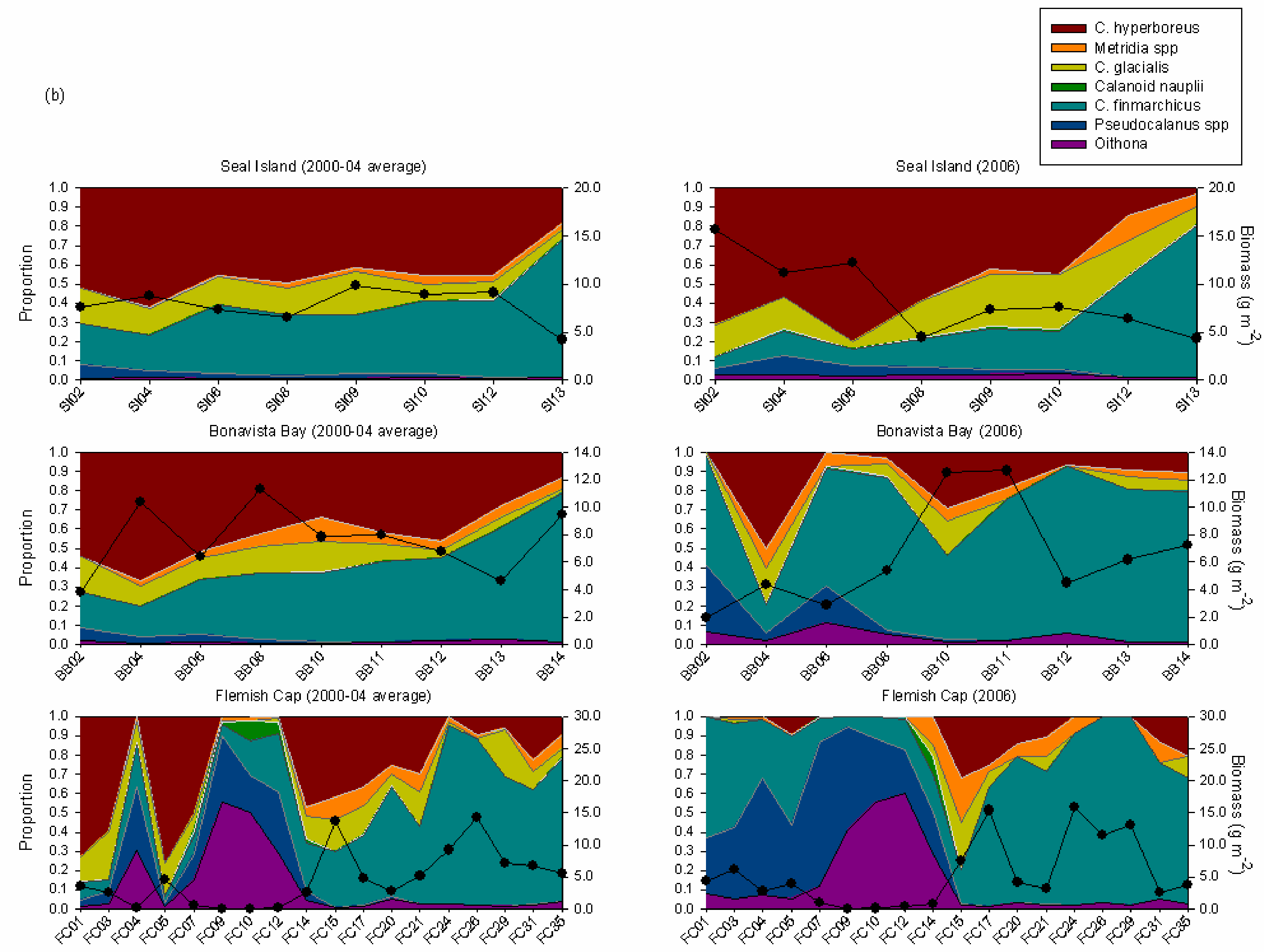


Figure 23. Spatial distribution in (a) abundance, (b) biomass, and species composition for the seven dominant copepod taxa collected along oceanographic transects sampled in the summer surveys. The left-hand panels show the average distribution for 2000-04 while the right-hand panels shows the observations for 2006.

Figure 23 (Cont'd.)



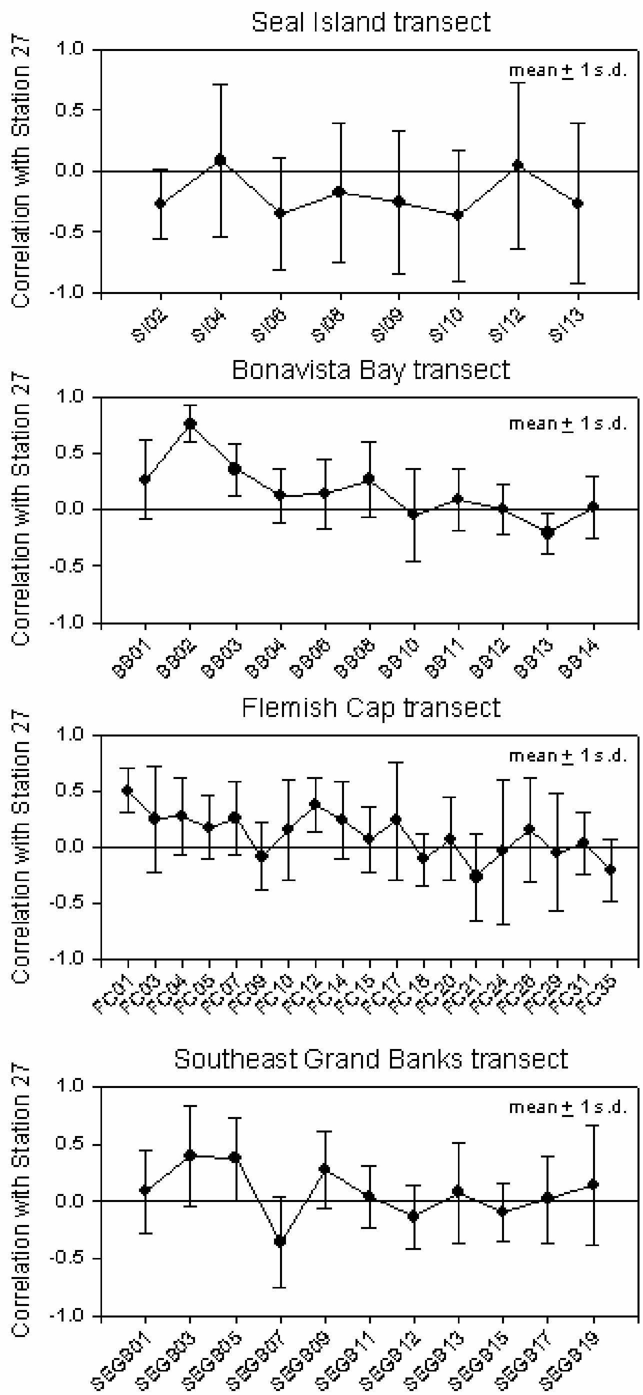


Figure 24. Average correlation of deseasonalized log-transformed zooplankton abundance from each station along the four oceanographic transects. Errors bars represent one standard deviation. The deseasonalized estimates were obtained by subtracting the observation for each station and survey from station-specific seasonal mean (2000-05). The averages are based on data from the seven dominant copepod taxa for the region.