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**Newfoundland and Labrador Region**

**Optical, chemical, and biological oceanographic conditions on the Newfoundland  
and Labrador Shelf during 2011-12**

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## Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

Research documents are produced in the official language in which they are provided to the Secretariat.

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## ABSTRACT

Across the region, surface inventories of nitrate were generally higher during first half of 1999-2011 period and lower during the second half. There has been a general decline in bottom inventories throughout that period. Phytoplankton standing stock has been highly variable from year-to-year but overall abundance was generally low in 2011. Satellite imagery indicates a high degree of coherence in the interannual variations in the timing and magnitude of spring phytoplankton bloom. After a period with progressively earlier blooms, conditions in 2011 and 2012 were near normal in the north and late in the south. Zooplankton abundance has shown a general increase during the decade, with some taxa (e.g., *Calanus finmarchicus*, *Oithona atlantica*, *Centropages*, *Metridia longa*) demonstrating more consistent upward trends than others. Changes in community composition and overall abundance appears to be the result of variations in movement of water masses, with the balance on/off shelf communities appearing to be more important on the Newfoundland Shelf while the balance between warm and cold water species being more significant on the Grand Banks. We noted some significant changes in the phenology of *Calanus finmarchicus* and *Pseudocalanus* spp. based on observations at S27, our high frequency monitoring site but the causes and consequences of these changes need to be explored further.

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## Conditions océanographiques biologiques, chimiques et optiques sur la plate-forme continentale de Terre-Neuve-et-Labrador en 2011-2012

### RÉSUMÉ

Dans la région, les concentrations de nitrate dans les eaux de surface étaient généralement plus élevées au cours de la première moitié de la période s'échelonnant de 1999 à 2011 que pendant la deuxième moitié. On a constaté un déclin général des concentrations au fond au cours de cette période. Le stock de phytoplancton a affiché d'importantes variations d'une année à l'autre, mais son abondance globale était généralement faible en 2011. L'imagerie satellitaire indique un fort lien dans les variations interannuelles en ce qui a trait à la période et à l'ampleur de la prolifération printanière du phytoplancton. Après une période de proliférations toujours plus précoces, les conditions en 2011 et en 2012 se situaient près de la normale dans le nord, et plus tard dans le sud. Dans l'ensemble, l'abondance du zooplancton a augmenté pendant la décennie, certains taxons (p. ex., *Calanus finmarchicus*, *Oithona atlantica*, *Centropages*, *Metridia longa*) affichant des tendances à la hausse plus marquées que d'autres. Les changements dans la composition de la communauté et l'abondance globale semblent découler des variations dans le mouvement des masses d'eau; l'équilibre entre les communautés sur le plateau et celles au large de celui-ci semble plus important sur le plateau de Terre-Neuve, tandis que l'équilibre entre les espèces d'eau chaude et les espèces d'eau froide semble plus significatif sur les Grands Bancs. On a remarqué des changements considérables dans la phénologie de *Calanus finmarchicus* et de *Pseudocalanus sp.* d'après des observations effectuées à S27, le site de surveillance à haute fréquence, mais les causes et les conséquences de ces changements doivent être étudiées plus en profondeur.

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## INTRODUCTION

The Atlantic Zone Monitoring Program (AZMP) was implemented in 1999 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 overall aim is to identify fundamental relationships among elements of the planktonic ecosystem and establish how they respond to changes in environmental drivers.

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

To the extent possible, sample collection and processing conforms to established standard protocols (Mitchell et al. 2002). Non-standard measurements or derived variables are described below.

### SAMPLE COLLECTION

Three seasonal oceanographic surveys were conducted in the Newfoundland and Labrador Region during the 2011 and 2012 calendar years, in addition to day-trips to the fixed coastal station (S27). In general, the major oceanographic section stations and S27 were occupied seasonally during 2011 and 2012 (Fig. 1; Table 1). We achieved near bi-weekly to monthly occupations of S27 during January-December in 2011 and 2012 although sampling during the winter months was largely limited to physical oceanographic measurements and zooplankton net collections.

### ANALYSIS

Two simple indices of the physical structure (vertical) of the water-column were computed for comparison with optical properties; mixed-layer and stratification. The mixed layer depth was determined from observations of the maximum density gradient (gradient<sub>z</sub> (sigma-t)). The stratification index (SI) was calculated as:

$$SI = (\text{sig-t}_{50} - \text{sig-t}_{z_{\min}}) / (50 - z_{\min})$$

where sig-t<sub>50</sub> and sig-t<sub>z<sub>min</sub></sub> are interpolated values of sigma-t for the depths of 50 m and z<sub>min</sub> (the minimum depth of reliable CTD data ); typically z is around 5 m and always less than 9 m.

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<sub>d</sub>), which is determined by dissolved and coloured substances and particulate matter in seawater. The vertical attenuation coefficient (K<sub>d</sub>) was derived from in-water light extinction measurements using a CTD-rosette mounted PAR (photosynthetic active radiation) meter. The downward

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vertical attenuation coefficient of PAR ( $K_{d- PAR}$ ) 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:

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

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 observations 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 50m. The estimate of euphotic depth (ca. depth of 1 % incident PAR) was computed from:

$$Z_{eu} (m) = 4.6 / K_d$$

We substituted  $K_{d\_chl a}$  when  $K_{d- PAR}$  was not available to compute the euphotic depth.

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

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

for S27, where *Density* is in units of  $m^{-2}$ ,  $\alpha$  is the intercept,  $\beta$  and  $\delta$  are categorical effects for year and month effects, and  $\varepsilon$  is the error, and

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

to derive an estimate of the interannual variations based on all occupations of the transects, where  $\delta$  takes into account the effect of station location and  $\gamma$  takes into account variation among seasons. Density, either in terms of numbers or biomass, was log-transformed to deal with the skewed distribution of the observations. In the case of zooplankton, one was added to the *Density* term to include observations where no animals of a given taxa were counted in the sample. Average integrated physical variables, and inventories of nutrients and chlorophyll were not transformed. An estimate of the least-squares means based on type III sums of squares was used as the measure of the overall year effect.

## SATELLITE REMOTE-SENSING OF OCEAN COLOUR

Satellite observations provide a comprehensive spatial and temporal view of surface phytoplankton biomass. We combined Moderate Resolution Imaging Spectrodiometer (MODIS) data obtained continuously from January 2004 until December 2011 with Sea-viewing Wide Field-of-view Sensor (SeaWiFS) from September 1997 until December 2009 to construct composite time series of surface chl  $a$  across 10 statistical sub-regions in Newfoundland and Labrador, extending from Hudson Strait down to the Southeast Shoal (see Fig. 2 for locations). Basic statistics (mean, range, standard deviation, etc.) are extracted from two week average 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. Data from both satellite sensors was provided by the Bedford Institute of Oceanography<sup>1</sup> (Dartmouth, NS)

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<sup>1</sup> <http://www.bio.gc.ca/science/newtech-technouvelles/sensing-teledetection/index-eng.php>

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and we computed an average value of surface chlorophyll *a* during the overlap period of satellites. Data gaps greater than one month in duration were excluded for the analyses.

We used the shifted Gaussian function of time model to describe the characteristics of the seasonal cycle of phytoplankton production based on the combined satellite data (Zhai et al. 2011). Five different metrics were computed using satellite composite data from January through the end of August including background chlorophyll *a* concentration ( $\text{mg m}^{-3}$ ), the integral of chlorophyll *a* concentration under the Gaussian curve ( $\text{mg m}^{-2} \text{d}^{-1}$ ), the time of the spring bloom peak (Julian day), duration of the spring bloom cycle (days) and the initiation time of the spring bloom (Julian day). In addition, we computed normalized annual anomalies for each of the different bloom metrics to evaluate evidence of time trends among the different statistical sub-regions.

## OBSERVATIONS

### MIXED-LAYER, STRATIFICATION INDEX AND OPTICAL PROPERTIES—FIXED STATION

The seasonal development of the mixed layer in 2011-12 indicated greater mixing down to ca. 150m depths during the winter-spring period although the number of observations was limited at S27 (Fig. 3). The minima in mixed-layer depth in 2011-12 occurred in May rather than July, as observed in most years (1993-2010). The onset of deepening of the mixed-layer that begins in early autumn was similar to the average conditions. Stratification of the water-column at S27 followed the normal seasonal development during the first-half of 2011-12 but was somewhat weaker during the second half of the year relative to the long-term climatology (Fig. 3).

We were unable to track the early seasonal development of the photic indices at S27 in 2011-12 because of the limited number of observations during winter. Relatively deeper penetration of incident light (lower vertical attenuation coefficients) was evident during late spring, summer and early autumn compared to average conditions in previous years (2000-10) (Fig. 3).

### NUTRIENTS—FIXED STATION

The vertical distributions of inorganic nutrients (nitrate, silicate, and phosphate) included in the observational program of the AZMP show strong seasonal co-variation (Petrie et al. 1999). For this reason, and because the availability of nitrogen and silicate is most often associated with limiting the growth of phytoplankton, more emphasis in this report was placed on variability in these nutrient. The vertical structure of nitrate (combined nitrate and nitrite hereafter referred to as nitrate) shows dynamic seasonal changes in the water column at S27 (Fig. 4). We were unable to capture the complete dynamic range of nutrient concentrations in 2011 and 2012 during winter and early spring at S27 because of limited sampling. Concentrations of nitrate in early to mid-April were below 2  $\text{mmol m}^{-3}$  in the upper 30 m, which indicated that the spring bloom had occurred previously. Concentrations of nitrate were depleted rapidly in the upper 50 m to < 1.0  $\text{mmol m}^{-3}$  by late April and remained relatively low throughout the summer in 2011-12. The nutricline extended down to ca. 60-75 m in May but shoaled to 50 m during the summer and early autumn in both years, which was consistent with previous observations. The extent of nitrate uptake in the upper water-column was noticeably higher in 2010-12, compared to previous years (Fig. 4). A small shoaling in the depth of the nutricline coincided with the development of the autumn phytoplankton bloom. This was followed by an increase in nutrient concentrations in the upper parts of the water column during the late fall–early winter period, a time when stratification breaks down and deep mixing of the water column normally occurs.



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Changes in silicate concentrations at S27 follow the same general dynamic seasonal pattern as for nitrate with rapid uptake in late March-early April but with greater nutricline depths, approaching 100 m, in most years (Fig. 5). Shoaling of the nutricline is also apparent during the summer and early fall, similar to the pattern observed for nitrate. The timing of replenishment of silicate levels normally takes place in the late fall but varied considerably from year-to-year relative to the pattern of nitrate cycling (Fig. 5).

The inventories of nutrients are strongly influenced by seasonal biological processes operating throughout the upper water-column. The inventories of nitrate at S27 in the upper 50 m in 2011-12 was only slightly above the 2010 record-low value while the reverse was the case for silicate levels (Fig. 6). The upper water-column inventories of these major macro-nutrients are normally tightly coupled during the spring and fall blooms. The cycling of nitrate appears to be partly decoupled from that of silicate in recent years. The explanation for this apparent difference in utilization and recycling of these nutrients in recent years is unclear but, may be related to a variety of factors such as changes in phytoplankton community, and contributions of different water masses. The 0-50 m annual nitrate inventory anomalies were consistently negative since 2009 with the largest deficit in 2010 (Fig. 6). The overall trend in upper water-column silicate inventories at S27 have remained relatively stable over the past decade but have also been in decline in recent years with the largest negative anomaly in 2012. The deep (50-150 m) inventories of nitrate and silicate at S27 show large short-term and interannual variations but with limited defined and repeatable seasonality (Fig. 7). The deep inventories of silicate and nitrate have also declined in recent years at S27 compared to earlier years. Persistent negative anomalies have been observed in deep nitrate inventories since 2009 while silicate levels have been in decline since 2010 with the largest negative anomaly in 2012 (Fig. 7). Although the cause for the observed decline in both shallow and deep nutrient inventories in recent years is unknown at this time, the lower levels will likely impact future primary productivity if this trend continues.

## **PHYTOPLANKTON BIOMASS–FIXED STATION**

We were unable to identify the full extent of the spring bloom in 2011 at S27 because there was limited biological sampling during winter-early spring, as noted previously. One noticeable trend in the seasonal development of phytoplankton blooms at S27 has been the shift to earlier initiation of the spring bloom from April-May to late-March-April, further emphasizing the need of higher frequency sampling throughout the year in order to monitor changes in timing and evaluate the full extent of the production cycle. The timing, magnitude and duration of the 2011-12 spring blooms appeared to be less extensive compared to traditional spring blooms that occurred during the April-May period (Fig. 8). The high levels of phytoplankton biomass associated with spring blooms during the early part of the monitoring program have not been apparent in recent years despite the high levels of nutrient depletion in the upper water column we have observed at S27 in recent years (Figs. 6-7). This suggests that we may have missed the early part of the production cycle based on limited sampling or that nutrient enrichment of surface waters (in addition to incident light levels) was insufficient to support the high levels of primary productivity that had observed during the development of the spring bloom during the earlier part of the observations series from S27. Peak chlorophyll *a* levels occurred in 1999 and inventories have been in gradual decline over the past decade and recent years (Fig. 9).

## **SHELF SECTIONS–NUTRIENTS AND PHYTOPLANKTON BIOMASS**

Scorecards using normalized, seasonally-adjusted annual anomalies of nutrient availability and phytoplankton biomass along the different sections and S27 were used to assess long-term trends. Lower than average shallow and deep-water nutrient concentrations and phytoplankton biomass persisted in 2012 on all ocean sections and S27 except for the southeast Grand Bank,

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which was near normal (Fig. 10). Large reductions in both shallow and deep nutrient inventories were detected in 2009 across most of the Newfoundland and Labrador Shelf, continuing a negative trend observed in recent years (Fig. 10). Significant reductions in phytoplankton biomass were also observed in 2011 along the southern sections on the Newfoundland (southeast Grand Bank and Flemish Cap) and Labrador (Seal Island) Shelves. Interannual variability in upper 50m nutrient (silicate and nitrate) inventories show coherent changes during the time series with no obvious long-trends (Fig. 11). In contrast, deep-water inventories have been gradually decreasing over the past decade with more rapid reduction apparent since 2009, particularly for nitrate (Fig. 11). Although record low levels of phytoplankton biomass were observed along the southern sections in 2011 and continuing low levels into 2012 for all areas, no clear long-term trend was detected in phytoplankton biomass along the different ocean sections over the period of AZMP observations (Fig. 11).

## REMOTE SENSING OF OCEAN COLOUR

Satellite ocean colour (SeaWiFS and MODIS) data provides large-scale images of surface phytoplankton biomass (chlorophyll *a*) over the whole of the NW Atlantic not possible for conventional vessel-based sampling. Using two-week satellite composite images of sub-regions off Newfoundland and Labrador supplements our ship-based observations and provides seasonal coverage and a large-scale context with which to interpret our survey data (Fig. 12). The ocean colour imagery provides information about the timing and spatial extent of the spring and autumn blooms but does not provide information of the dynamics that take place below the top few meters of the water column. Subsurface information is achieved using the high frequency sampling at S27 and the broad scale oceanographic surveys.

The early development of patchy surface blooms had occurred on the south-western areas of the Grand Banks by early March in 2011 and 2012 (composite imagery not shown). The spring bloom intensified rapidly to cover the entire Grand Banks and northeast Newfoundland Shelf by late April, with chlorophyll *a* concentrations in excess of  $10 \text{ mg m}^{-3}$ . By the time of our spring oceanographic survey, in late April-early May 2011, chlorophyll *a* concentrations had declined to near-background levels over much of the Grand Bank, with surface blooms being confined to the northeast Shelf (Fig. 1). During the 2011 summer survey, near surface concentrations of chlorophyll *a* were at background levels over much of the northwest Atlantic, with the exception of the northern tip of the Labrador Shelf–Hudson Strait (Fig. 1). Extensive cloud cover during the autumn surveys in 2011 and 2012 in late November limited our capacity to detect the areal extent of surface blooms (particularly north of the northeast Newfoundland Shelf). During the autumn surveys, chlorophyll concentrations were  $\sim 1 \text{ mg m}^{-3}$  over much of the Grand Banks, with a few high concentration patches observed on the southwestern Grand Banks (St. Pierre and Green Bank), southeast Shoal and in Slope waters (Fig. 1). During the 2012 spring survey (which took place earlier compared to 2011), higher chlorophyll *a* concentrations were restricted to the southwestern Grand Bank, Flemish Cap, and northeast Shelf, with much of the Grand Bank near background levels (Fig. 1). Near surface chlorophyll *a* concentrations were at background levels over much of the survey area in summer 2012 with only small areas along the coastal regions showing any elevated levels.

At larger scales, observations from 10 sub-regions off Newfoundland and Labrador indicated that the magnitude of surface phytoplankton blooms detected by SeaWiFS-MODIS satellites was generally weak in 2012 relative to the previous year (Fig. 12). In addition, surface blooms occurred earlier in many of the sub-regions, were less intense and in many cases shorter in duration in 2011-12 relative to the patterns noted previously. We observed a strong shift to earlier timing of the spring bloom in 2010 along the northeast Newfoundland Shelf and Grand Bank. The occurrence of autumn blooms, which are sometimes not captured well by conventional sampling, was supported by the high-resolution SeaWiFS-MODIS imagery across

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all statistical sub-regions. The satellite data indicate stronger surface chlorophyll *a* concentrations across most sub-regions during autumn in recent years (Fig. 12).

The standardized scorecard anomalies inferred from the combined SeaWiFS and MODIS satellite imagery showed some interesting patterns across the statistical sub-regions (Fig. 13). The annual anomalies were predominately negative in 2012 across 9 of 10 of the sub-regions. This is in contrast to elevated production observed over the Newfoundland and Labrador Shelves in 2008-11. A shift to earlier timing of the spring bloom is evident in the increased frequency of negative anomalies since 2010 across many of the sub-regions. In addition, the duration of the spring bloom has been in decline since 2010 except for the most southerly sub-regions (Fig. 13).

## TRENDS ON OCEANOGRAPHIC SECTIONS—ZOOPLANKTON

Small copepods (Fig. 14)—Species that contribute to this group can be separated into two categories: those that have shown a general increase in abundance during the period 1999-2012, and those which have declined. Increases have been most notable from the southeast Grand Banks to the Bonavista Bay sections whereas the trends have been more variable on the Seal Island section, probably because of the limited sampling. *Microcalanus* sp., *Oithona atlantica*, *Oithona similis*, *Centropages* sp., and *Spinocalanus* sp. have shown positive trends during the last thirteen years, although *Microcalanus* sp. and *Centropages* sp. have both declined to very low levels on the southeastern Grand Banks section in 2012. *Pseudocalanus* sp. and *Oncaea* sp., although generally abundant in the last few years, have shown considerable variability over time and among sections, with the former being at its lowest level on the Flemish Cap section in 2011. *Chiridius gracilis*, *Acartia* sp. and *Paracalanus parvus* were all at low levels in 2011, which in most cases followed a declining trend over many years, although *Acartia* sp. did show some recovery in 2012. It is noteworthy that there appears to have been an abrupt change in abundance of *Chiridius gracilis* and *Acartia* sp. sometime between 2004 and 2006, with the change being most pronounced on the Bonavista and Seal Island sections (hereafter referenced as the northern ecoregion; Pepin et al. 2010) in 2006.

Large copepods (Fig. 15)—*Calanus finmarchicus* is numerically dominant among the species of large copepods that are widespread across the region. On the Grand Banks and Flemish Cap sections (hereafter referenced as the southern ecoregion; Pepin et al. 2010), the trend in abundance of this species since 1999 has been toward increasing abundance. Abundance in the northern ecoregion has shown fluctuations, with a peak in 2004-2006, with differing levels of variability between the Bonavista and Seal Island sections.

*Calanus glacialis* is a cold water species that occurs principally over the continental shelf. It is most abundant on the Seal Island section, where the pattern of variation has been relatively similar to that of *C. finmarchicus*, peaking in 2006 after which abundance had declined until a five-fold increase occurred from 2011 to 2012. Abundance of this species on the Bonavista section has shown very limited inter-annual variability but there has been a persistent decline in the southern ecoregion since the start of the century.

*Calanus hyperboreus*, the largest of the three *Calanus* species, has shown oscillations in abundance on the southeast Grand Banks section with a general overall decline since 2002. Although variable in abundance on the Flemish Cap section, the trend in the northern ecoregion had been toward an increase from 1999 to 2003 after which there interannual variations have been limited.

*Metridia* spp. (which consists of two species *Metridia lucens* and *Metridia longa*) is most abundant in the northern most part of the region. Although there has been no apparent trend on the Seal Island section, there has been a general increase in abundance along the Flemish Cap

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and Bonavista sections. Abundance of this taxa on the southern Grand Banks peaked in 2009 and reached a record low in 2012.

Large calanoid nauplii, which are most abundant on the two northern sections, demonstrate high interannual variations in abundance. The high variability from year-to-year and among sections is likely a reflection of changes in the timing of reproduction by the adults and variable survival rates of the nauplii, which may be dependent on environmental conditions.

Meroplankton and other selected taxa (Fig. 16)–The abundance of meroplankton (larval stages of *Balanus* spp., bivalves and polychaetes) generally demonstrate a high degree of inter-annual variability in abundance probably because of variations in the timing of reproduction by the adults and fluctuations in larval survival. There has been a long-term decline in the abundance of *Balanus* spp. on the Grand Banks section since 1999, and on the Seal Island section since 2005, while abundance has remained low on the Flemish Cap and Bonavista sections, although there appears to have been a significant increase in abundance in 2012 in the northern ecoregion. Other meroplankton have not exhibited anything more than short-term and localized trends. Ostracods have generally shown an increasing trend since the inception of AZMP although their abundance in 2011-12 was well below that of peak years along some sections. The abundance of pelagic gastropods declined substantially in 2011 along the Grand Banks, Flemish Cap and Bonavista sections with some recovery apparent on the Grand Banks in 2012. Abundance on the Seal Island section has remained low since 2006. Larvaceans were at high levels of abundance on the Grand Banks in 2011 and 2012.

Carnivorous zooplankton (Fig. 17)–This group consists of a mixture of taxa that feed predominantly on mesozooplankton. The abundance of the two gelatinous zooplankton species, *Aglantha digitale* and *Pelagia noctiluca*, has generally been decreasing along most oceanographic sections since 2003-2006. The strength of and variability about the trend varies but the general pattern appears to be consistent. The same pattern has also been apparent for hyperiid amphipods, which have also become less abundant since that time. In contrast, the abundance of *Euchaeta* sp., euphausiids (largely juveniles), and *Sagitta* sp. has generally increased since the inception of the sampling program, although as with other carnivorous zooplankton the strength and variability of the trend differs among species and sections.

General patterns of variation (Fig. 18)–We combined the time series from the taxa included in Figs. 14-17 to investigate general patterns of variation using principal components analysis of the variance-covariance matrix, an exploratory multivariate technique that aims to identify the significant trends among the variables. Because of similarities in the patterns of variation among oceanographic sections, separate analyses were performed for the northern and southern ecoregions based on preliminary analyses. The first two principal components (PC) explained 41 % and 19 % of the variation in the time series of the 22 taxa included in the analyses. Community composition in the northern ecoregion (Newfoundland Shelf) demonstrates a strong cross-shelf gradient (Pepin et al. 2011b) which is reflected in the first PC, along with the shifting balance that may be caused by variations in transport of Labrador Sea water onto the shelf. Interannual variations in abundance are apparent in the second PC, with the early part of the decade generally having low scores while 2004, 2006 and 2010 have generally higher scores. The analysis of the data for the 28 taxa from the southern ecoregion (Grand Banks) revealed fluctuations in the abundance of warm and cold water species on the first PC (58 %) while scores along the second PC (13 %) reflected general trends during the decade.

## **TRENDS–TIME SERIES DATA FROM S27**

The high frequency sampling site S27 serves to provide insight into the factors driving seasonal and interannual fluctuations in abundance of key oceanographic variables and zooplankton taxa. Gaps in data collection exceeding 3 weeks are frequent between January and March and

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between early August and late September, which impacts our ability to infer the significance of variations in population dynamics that may span those intervals. The site is located in inner branch of the Labrador Current and the patterns of variations in the abundance of most chemical and biological variables are likely to reflect principally changes occurring on the inner portion of the Newfoundland Shelf, with variable contributions from offshore areas making inferences that much more complex (Pepin et al 2013).

Copepodite biomass in 2011, based on the stage dependent abundance and weight of 5 dominant taxa (*Calanus*, *Pseudocalanus*, and *Metridia*) and that of the adults of three genera of small copepods (*Oithona*, *Centropages* and *Temora*), was slightly below the long term average following a decline from the high levels measured in 2009 and reached the lowest value on record in 2012 (Fig. 19). *Microcalanus* spp. and *Metridia* spp. have demonstrated strong increases in abundance while *Sagitta* spp. has generally declined in abundance since the inception of AZMP (1999–2012) (Fig. 20). Most other abundant taxa from S27 appear to show fluctuations in abundance over shorter periods (~3–5 years) with no clear periodicity or associations among them. The decline in copepodite biomass since 2009 appears to be the result of declines in the overall abundance of late stages (C3–C6) of *C. glacialis* and *C. hyperboreus* (not shown). The strong seasonality in species-specific biomass cycles appears to have been maintained over the duration of the time series (Figure 21) but we have not developed comprehensive analytical approaches aimed at quantifying possible fluctuations that may have taken place between 1999 and 2012.

## COPEPOD PHENOLOGY

Previous reports (e.g. Pepin et al. 2011a) have noted a high degree of consistency in the general seasonal succession of stages of *C. finmarchicus* and *Pseudocalanus* spp. during the last decade. Here we provide a more comprehensive description of the seasonal cycle of abundance of individual stages for the two species. The average (2000–2009) seasonal cycle of *C. finmarchicus* at S27 shows evidence of two cohorts of adults. There is a broad peak in abundance of adults (CVI) that starts in January, peaks from mid-March to early-May which then declines until late August after which there is a plateau in the abundance of adults from September until the end of October (Fig. 22). In the spring, most adults are females whereas the ratio is closer to 2 females to every 1 male in the autumn. Stage I copepodites (CI) are abundant from late April until mid-September, with a peak from mid-June to mid-August (Fig. 22). The occurrence of CII is nearly coincident with that of CIs, largely because development times between stages are generally short. Peak abundance of stage III copepodites (CIII) is delayed until the end of June and the peak in abundance of stage IVs is delayed until early-September, which is much later than if calculated according to Corkett et al.'s (1986) estimates of food-saturated temperature-dependent development times based on 0-25m integrated temperature. Stage V copepodites at S27 have a broad peak in abundance from September until the end of February. In offshore areas, these animals would most likely have entered diapause during this time period. The rise in abundance of CVs is coincident with that of the second peak in adults at S27, consistent with the short development times at high temperatures for copepods not entering diapause (Pepin et al., unpublished data), but the period of high CV abundance persists for longer than that of the adults. This may indicate that CV copepodites are being transported from northern sources over an extended period of time. The second cohort is most strongly represented by the peak in abundance of adults during the autumn and a secondary peak in the abundance of CII–CIV in late December–early January, with a relatively smaller increase in the abundance of CVs in January which could reflect the persistence of the autumn peak in abundance (Fig. 22). Analysis of yearly patterns in abundance reveals that the twin cohorts of adults (CVI) reflects a significant shift in the phenology of *C. finmarchicus* starting approximately in 2005, when the fall cohort increases in

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prominence (Fig. 23). This is coincident with high abundances of CV in those years. Starting in 2007, the spring cohort of adults, which has not been preceded by high numbers of CV copepodites, appears to decline in relative abundance. These changes in phenology of late stage copepodites are not as readily apparent in the younger copepodite stages.

The seasonal succession of *Pseudocalanus* spp. has a substantial cohort of CV copepodites during January to March followed by a peak in the abundance of CVI adults (Fig. 24). CI and CII copepodites are abundant from April to August and June to August, respectively. CIII copepodites peak in abundance in June-July and are followed by a broad peak in the abundance of CIVs from August until December. CV copepodites start to increase in abundance starting in September or October, but it was not until 2005 or 2006 that a second cohort of CVI adults began to appear after periods of high abundance of CVs (Fig. 24). The shift in phenology of *Pseudocalanus* spp. is somewhat more dramatic than that of *C. finmarchicus* because the winter cohort of CVs appears to be prolonged in duration and the summer cohort has an earlier onset starting in 2005-06. There were also indications of an earlier appearance of CIII and CIV copepodites at that time. The possible drivers of these shifts in phenology are currently under investigation.

## DISCUSSION

The overall pattern of variation among the three trophic levels surveyed in this report (nutrients, phytoplankton biomass, and zooplankton abundance) does not reveal any clear association among trophic levels. Although nutrient inventories across the region are generally at record low levels, the abundance of phytoplankton fluctuates substantially from year-to-year and the general trends in zooplankton abundance indicate that most taxa are near or above their long term (1999–2012) average. However, the pattern of variation of each trophic level demonstrates a high degree of regional coherence, with northern and southern portions of the Newfoundland and Labrador Shelf generally showing similar changes from year-to-year or over longer time scales. This suggests that coherent large-scale processes may be influencing the dynamics of lower trophic levels at the regional level but that identifying the functional relationships with these processes is likely to require careful consideration of the broad variety of influential factors and of the possible complexity of interactions. The high degree of spatial stability in the structure of the NL shelf ecosystem (Pepin et al. 2010) and zooplankton community (Pepin et al. 2011b), may serve to explain the strong regional coherence in the pattern of variation of each lower trophic level. However, the lack of coherence among trophic levels and environmental indices over the short period of observations from our monitoring activities in the region suggests that concepts such as the trophic cascade may not be applicable given the information currently available.

Variations in the indices of nutrients, phytoplankton and zooplankton levels appear to show greater variability than the general indices used to describe the state of physical atmospheric and oceanographic conditions in the region. Our previous analyses (Pepin et al. 2011a) have shown that no single environmental variable demonstrated a widely consistent pattern of correlation with either nutrient inventories, phytoplankton abundance or with the wide diversity of zooplankton taxa. This should not be entirely unexpected. Over the last decade (2000-10) the physical environment of the Newfoundland Shelf showed the lowest overall variability relative to previous decades going back to 1950. Therefore the range of environmental conditions encountered in the lower trophic levels may be considerably less than what they are normally subjected to. There are indications from the high relative frequency of positive correlations between environmental and biogeochemical variables, particularly zooplankton, that there is some underlying driving relationship at play. However, to assume that simple functional relationships drive the patterns of variation in lower trophic levels presumes a level of isolation

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of the Newfoundland and Labrador Shelf that may be somewhat naïve. Connectivity of zooplankton populations across the northwest Atlantic (i.e., zonal or greater) likely plays a significant role in determining patterns of variations at the regional level. Including a consideration of the role of transport in understanding variations in the productivity of lower trophic levels in the region would, however, require some knowledge of upstream conditions, such as those in the northern and eastern Labrador Sea. This may also require that analyses stratify information among water masses rather than the section-by-section approach currently being applied.

Exploratory analyses (Pepin et al. 2011a; this report) have revealed that no simple environmental relationships drive the patterns of variation in the nutrients, phytoplankton and the many zooplankton taxa considered in our assessment of the state of the ocean on the Newfoundland and Labrador Shelf and adjacent areas. The multivariate analyses presented in Figure 16 of this report suggest that there is a degree of consistency in the patterns of variation among zooplankton taxa but that the relative balance appears to be governed to a considerable extent by fluctuations in the physical features that constrain the large scale features in community structure (i.e., temperature, Labrador Current). If this interpretation is correct, our findings point to a need to gain a comprehensive understanding of the balance between the effects of local versus remote forcing on transport and the distribution of water masses in the region. However, knowledge of these drivers of change in biological features will have to be supplemented with analyses that seek to determine the factors that affect trophic interactions within water masses in order to establish the balance between physical and biological influences on changes in the productivity of lower trophic levels.

Comprehension of the mechanisms at play in the region will likely require insight that can only be gained from spatially-explicit models of key drivers and interactions. A mechanistic understanding of lower trophic level dynamics will only be achieved by coupling focused modeling approaches with empirical knowledge from continued, and possibly expanded, ocean monitoring.

## **SUMMARY**

- The minima in mixed-layer depth at S27 in 2011 and 2012 occurred earlier in May, in contrast to July observed in previous years.
- Stratification of the water-column at S27 tracked the normal seasonal development during the first-half of 2011-12 but, was somewhat weaker during the later part of the annual climatology.
- The extent of nitrate uptake in the upper water-column was noticeably higher at S27 in 2010-12 compared to previous years.
- In recent years, the annual mean upper water-column (<50 m) nitrate inventory at S27 has decreased by more than 50 % from the start of the program.
- The monthly < 50 m nitrate inventory anomalies were also consistently negative for almost all sampling months during 2010-12.
- The deep (50-150 m) inventories of nitrate at S27 continue to show a downward trend in 2011 and 2012 compared to earlier years, with levels only slightly above the record-low observed in 2010.
- The seasonal development of phytoplankton blooms at S27 was substantially earlier in recent years from the April-May to March-April period.

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- Integrated chlorophyll *a* levels at S27 were below normal conditions in 2011-12 and were at the lowest level observed in the time-series at ca. 50 % of the long-term average.
  - The annual mean anomalies of the monthly values of integrated chlorophyll *a* in 2011 were the lowest observed in the time-series and remained below average in 2012.
  - MODIS satellite imagery over the Newfoundland and Labrador Shelves indicated weaker spring and autumn blooms compared to previous years. In general, the surface blooms occurred later, were less intense and in many cases shorter in duration.
  - Metrics describing the seasonal dynamics of the production cycle based on satellite imagery have shown considerable variability over time with some coherent trends observed among the sub-regions during certain years.
  - The abundance of small copepods along ocean sections show divergent trends with a number of species that increased during 1999-2012, and another group of species that have declined steadily.
  - The abundance of *C. finmarchicus* has increased in recent years with the highest levels being recorded along the southern Grand Bank section in 2011 and the Flemish Cap section in 2012.
  - The abundance of *Calanus glacialis* and *Calanus hyperboreus* has shown long-term declines in abundance on the Flemish Cap and southeast Grand Bank starting in 2001, and shorter term declines on the Bonavista Bay and Seal Island section since 2009.
  - Copepodite biomass at S27 in 2011-12, based on the abundance of 8 dominant taxa, has demonstrated a consistent decline over time since the record high levels observed in 2009.
  - Analysis of yearly patterns in abundance reveals dramatic shifts in phenology of ecologically-important copepod species such as *C. finmarchicus* and *Pseudocalanus* spp. have occurred at S27 starting approximately in 2005, when the fall cohorts increase in relative abundance.

## ACKNOWLEDGMENTS

We thank Catherine Andrews, Wade Bailey, Eugene Colbourne, Joe Craig, Wayne Edison, Charlie Fitzpatrick, Paula Hawkins, Jennifer Hidgon, Fran Mowbray, Dave Senciall, Maitland Samson, Paul Stead, and Keith Tipple for their assistance at sea. We also wish to thank the many scientific assistants and technicians along with Coast Guard personnel aboard ships of opportunity who assisted with field collections. The expertise of Gerhard Pohle and Mary Greenlaw was important to the completion of this work.



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## REFERENCES

- Kirk, J.T.O. 1994. Light and photosynthesis in aquatic ecosystems. Cambridge University Press, 509 pp.
- Mitchell, M.R., Harrison, G., Pauley, K., Gagné, A., Maillet, G., and Strain, P. 2002. Atlantic Zone Monitoring Program Sampling Protocol. Can. Tech. Rep. Hydrogr. Ocean Sci. 223, 23 pp.
- Pepin, P., Cuff, A., Koen-Alonso, M., and Ollerhead, N. 2010. Preliminary delineation of marine ecoregions of the Newfoundland and Labrador shelves. NAFO SCR. 10/72, 24p.
- Pepin, P., Maillet, G.L., Fraser, S., Shears, T., Redmond, G. 2011a. Biological and chemical oceanographic conditions on the Newfoundland Shelf during 2009 and 2010. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/074, 51p.
- Pepin, P., Colbourne, E.B., and Maillet, G.L. 2011b. Seasonal variations in zooplankton community structure on the Newfoundland Shelf and western Labrador Sea. Progress in Oceanography. Doi:10.1016/j.pocean.2011.01.003
- Pepin, P., Han, G. and Head, E. J. 2013. Modelling the dispersal of *Calanus finmarchicus* on the Newfoundland Shelf: implications for the analysis of population dynamics from a high frequency monitoring site. Fisheries Oceanography. doi: 10.1111/fog.12028
- Petrie, B., Yeats, P., and Strain, P. 1999. Nitrate, silicate, and phosphate atlas for the Scotian Shelf and the Gulf of Maine. Can. Tech. Rep. Hydrogr. Ocean Sci. 203, 96 pp.
- Platt, T., Sathyendranath, S., Caverhill, C.M., and Lewis, M.R. 1988. Ocean primary production and available light: further algorithms for remote sensing. Deep-Sea Research, **35**: 855-879.

Table 1. Listing of AZMP Sampling Missions in the Newfoundland and Labrador Region in 2011 and 2012. The sections are Southeast and Southwest St. Pierre Bank (SESPB/SWSPB); Southeast Grand Banks (SEGB); Flemish Cap (FC); Bonavista Bay (BB); Funk Island (FI), Seal Island (SI); Avalon Channel (S27); Makkovik Bank (MB); Beachy Island (BI), Trinity Bay (TB), Smith Sound (SS), Hibernia (HIB), and the fixed station (S27). See Figure 1 for station locations for biological-chemical sampling 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.

<b>Mission ID</b>	<b>Dates</b>	<b>Sections/Fixed</b>	<b># Hydro Stns</b>	<b># Bio Stns</b>
TEL091	Apr 26-May 2, 2011	S27, SEGB, FC	32	24
TEL092	May 6-9, May 19-25, May 27, 2011	S27, FC, BB	30	30
TEL093	July 8-25, 2011	S27, FC, BB, WB, SI, MB, BI	83	50
HUD111	Nov 20-Dec 10, 2011	S27, SEGB, FC, BB, SI,	111	76
Fixed	Jan-Dec 2011	S27	37	19
TEL101	Apr 11-30, 2012	SESPB, SWSPB, SEGB, FC, HIB, BB, FI, S27, TB, SS	83	134
TEL104	July 9-27, 2012	FC, BB, WB, SI, MB, SS, S27	72	139
HUD112	Nov 20-Dec 9, 2012	S27, SEGB, FC, BB, SI, SWSPB, SESPB	104	70
Fixed	Jan-Dec 2012	S27	47	33

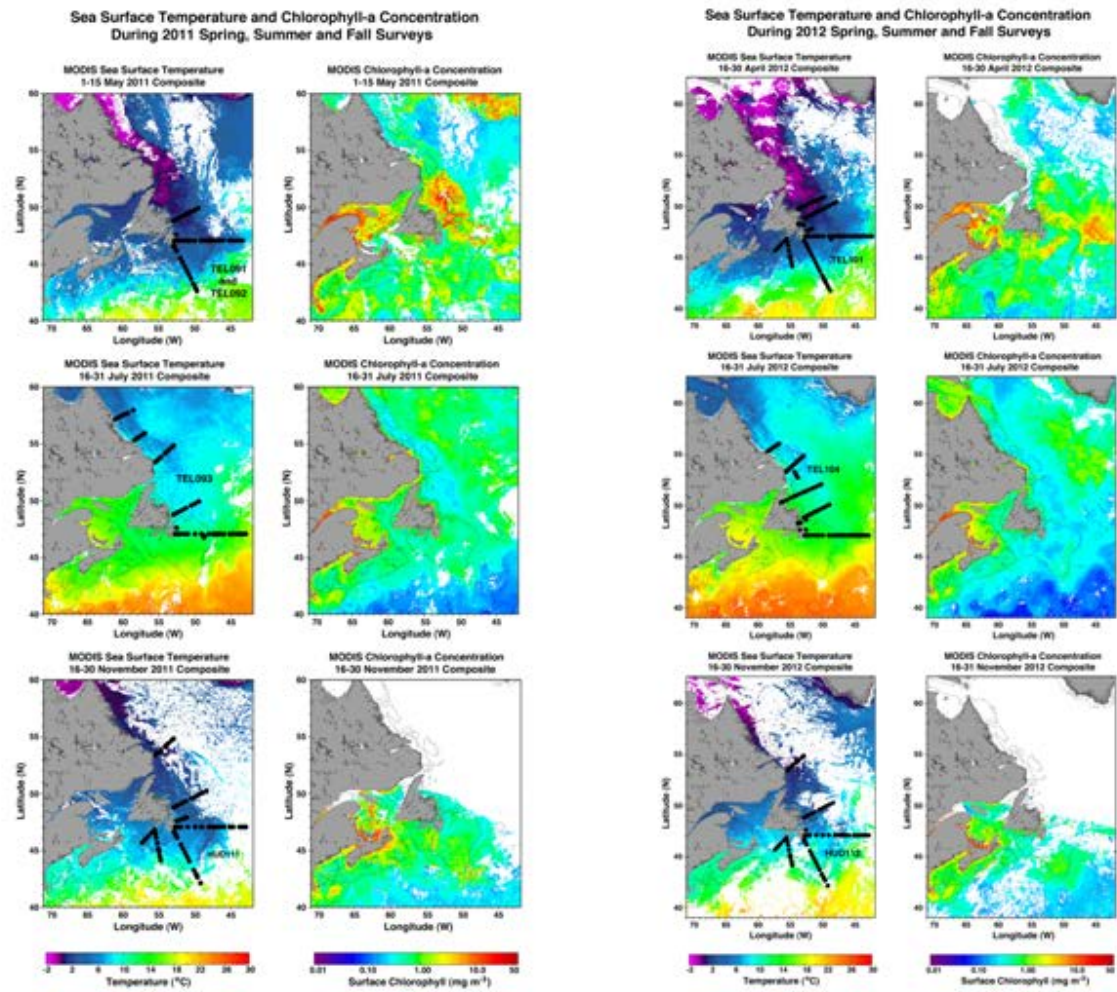


Figure 1. Station occupations during the 2011 (left panels) and 2012 (right panels) spring, summer, and fall section surveys, respectively. Station locations superimposed on twice-monthly sea-surface temperature composite images (left-side panels). Corresponding ocean colour composite images provided (right-side panels) for each sampling year.

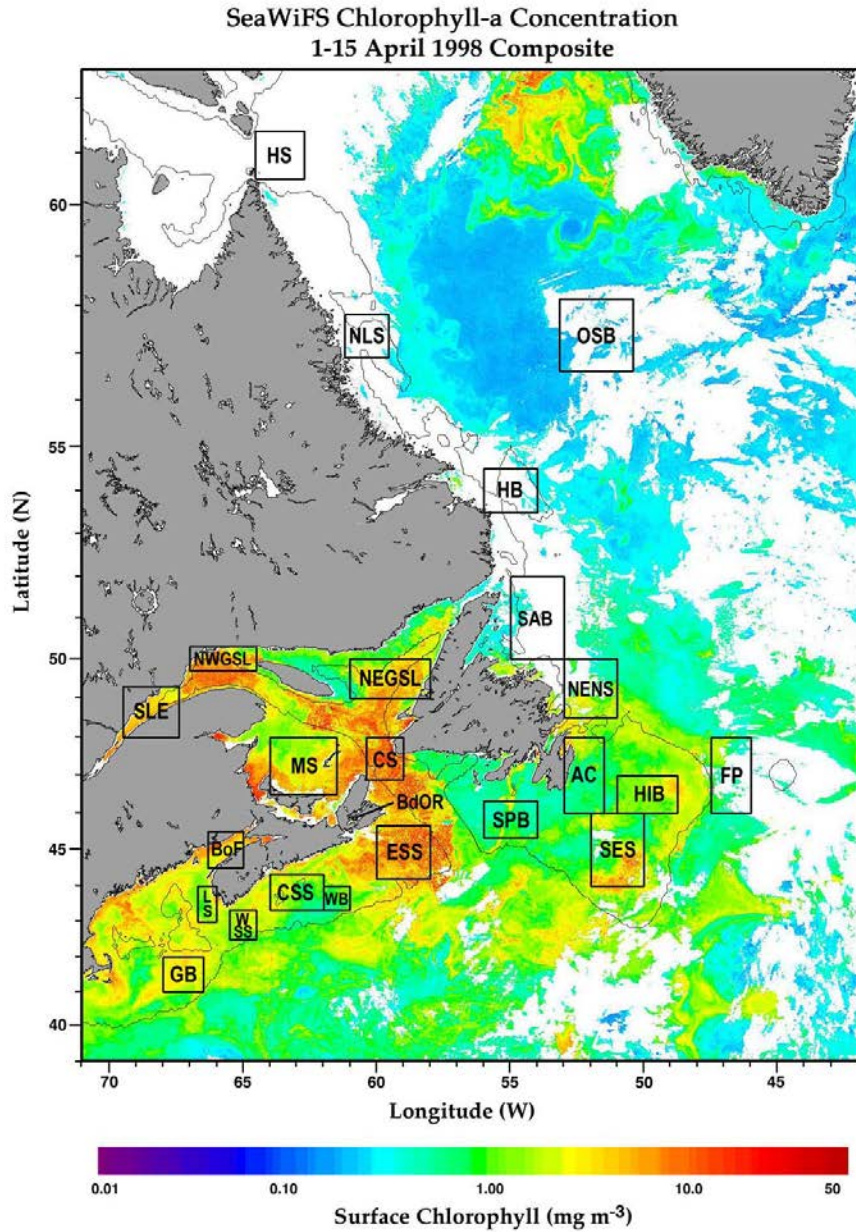


Figure 2. Statistical sub-regions in the Northwest Atlantic identified for spatial/temporal analysis of satellite ocean colour data in the Newfoundland and Labrador Region (underlined). AC–Avalon Channel; BdOR–Bras d’Or; BoF–Bay of Fundy; CS–Cabot Strait; CSS–Central Scotian Shelf; ESS–Eastern Scotian Shelf; FP–Flemish Pass; GB–Georges Bank; HB–Hamilton Bank; HIB–Hibernia; HS–Hudson Strait; LS–Lurcher Shoal; MS–Magdalen Shallows; NEGSL–Northeast Gulf of St. Lawrence; NENS–Northeast Newfoundland Shelf; NLS–Northern Labrador Shelf; NWGSL–Northwest Gulf of St. Lawrence; OSB–Ocean Station Bravo; SAB–St. Anthony Basin; SES–Southeast Shoal; SLE–St. Lawrence Estuary; SPB–St. Pierre Bank; WB–Western Bank; WSS–Western Scotian Shelf.

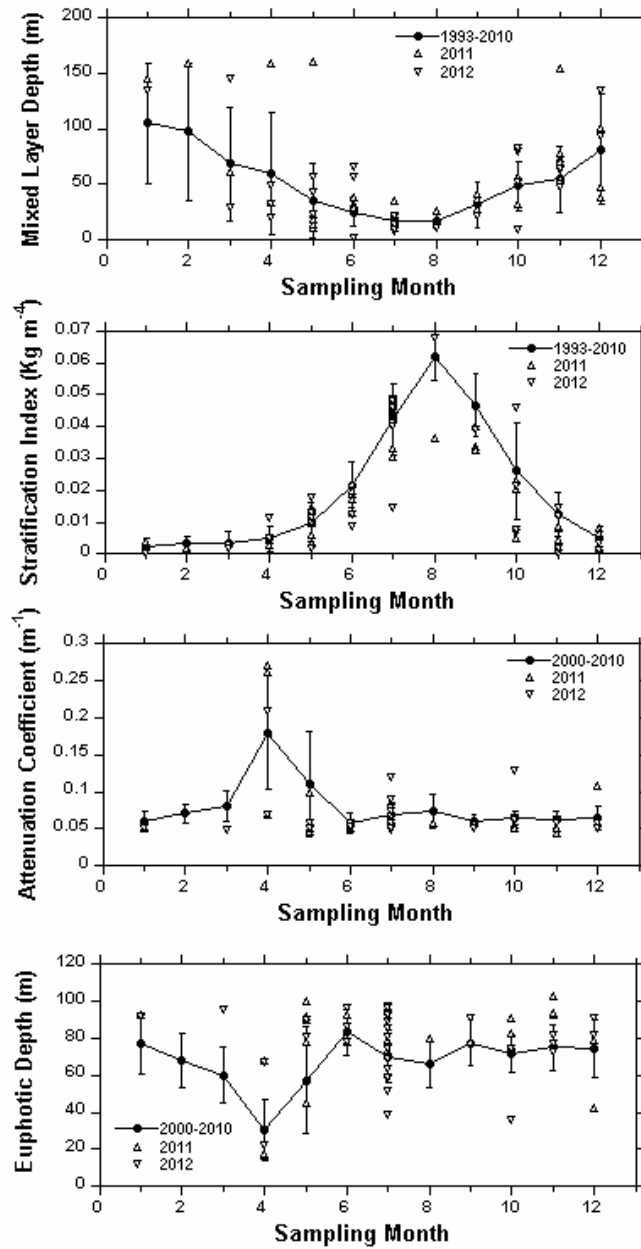


Figure 3. Physical (mixed layer depth; stratification index) and optical (vertical attenuation coefficient and euphotic depth) properties at S27. Year 2011 (upward open triangles) and 2012 (downward open triangles) compared with mean conditions (solid line) from 1933-2010 (physical indices) and 2000-2010 (optical indices). Vertical lines are standard deviations of annual means.

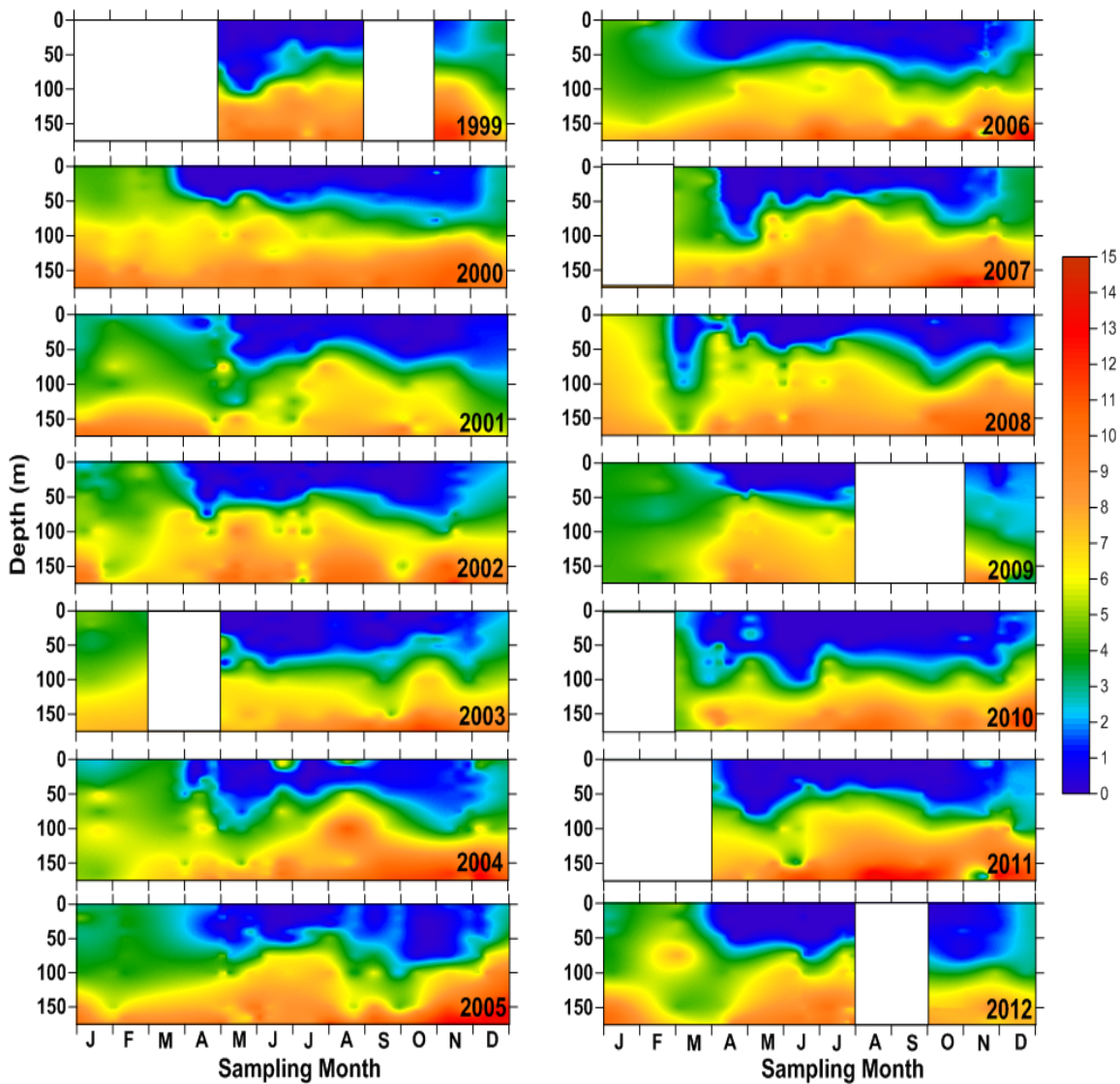


Figure 4. Time series of vertical nitrate concentration (mmol m<sup>-3</sup>) at S27 during 1999-2012. Sampling gaps > 2 consecutive months are blocked out in white.



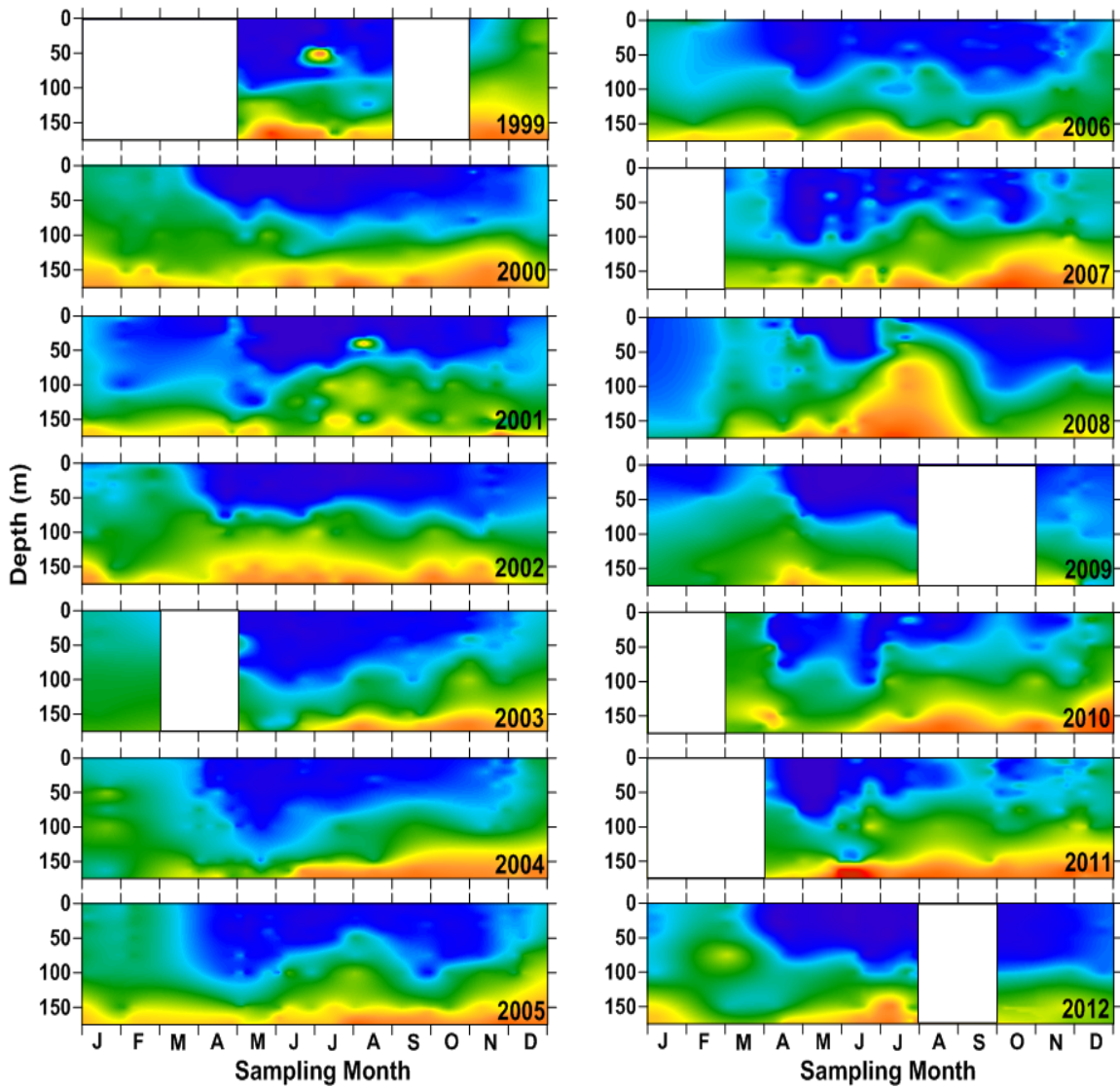


Figure 5. Time series of vertical silicate concentration ( $\text{mmol m}^{-3}$ ) at S27 during 1999-2012. Sampling gaps  $> 2$  consecutive months are blocked out in white.

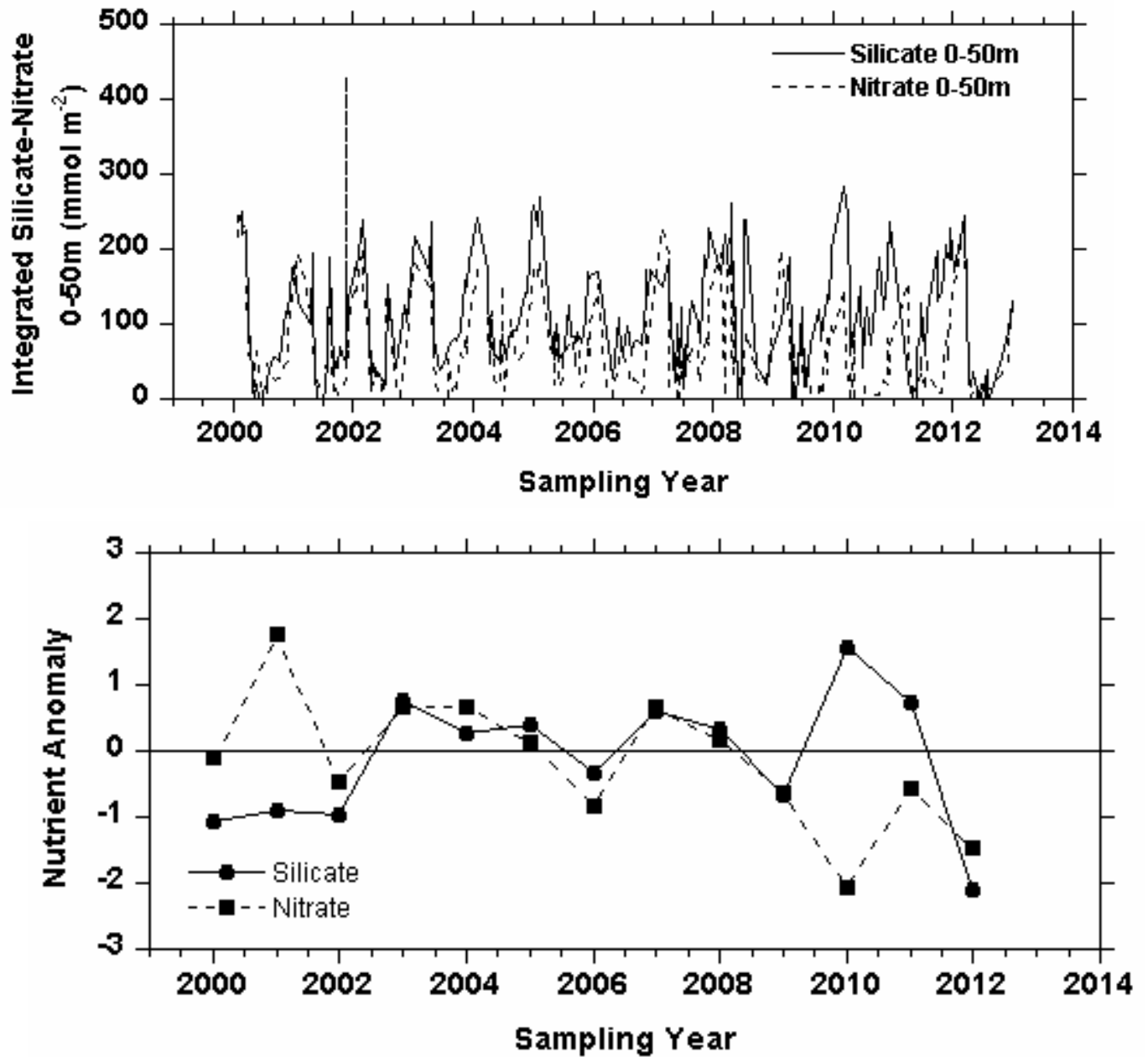


Figure 6. Time series of silicate and nitrate (0-50 m) inventories at S27, top panel. Bottom panel; least squares annual anomaly time-series of 0-50 m silicate and nitrate inventories at S27 (2000-10 reference period).



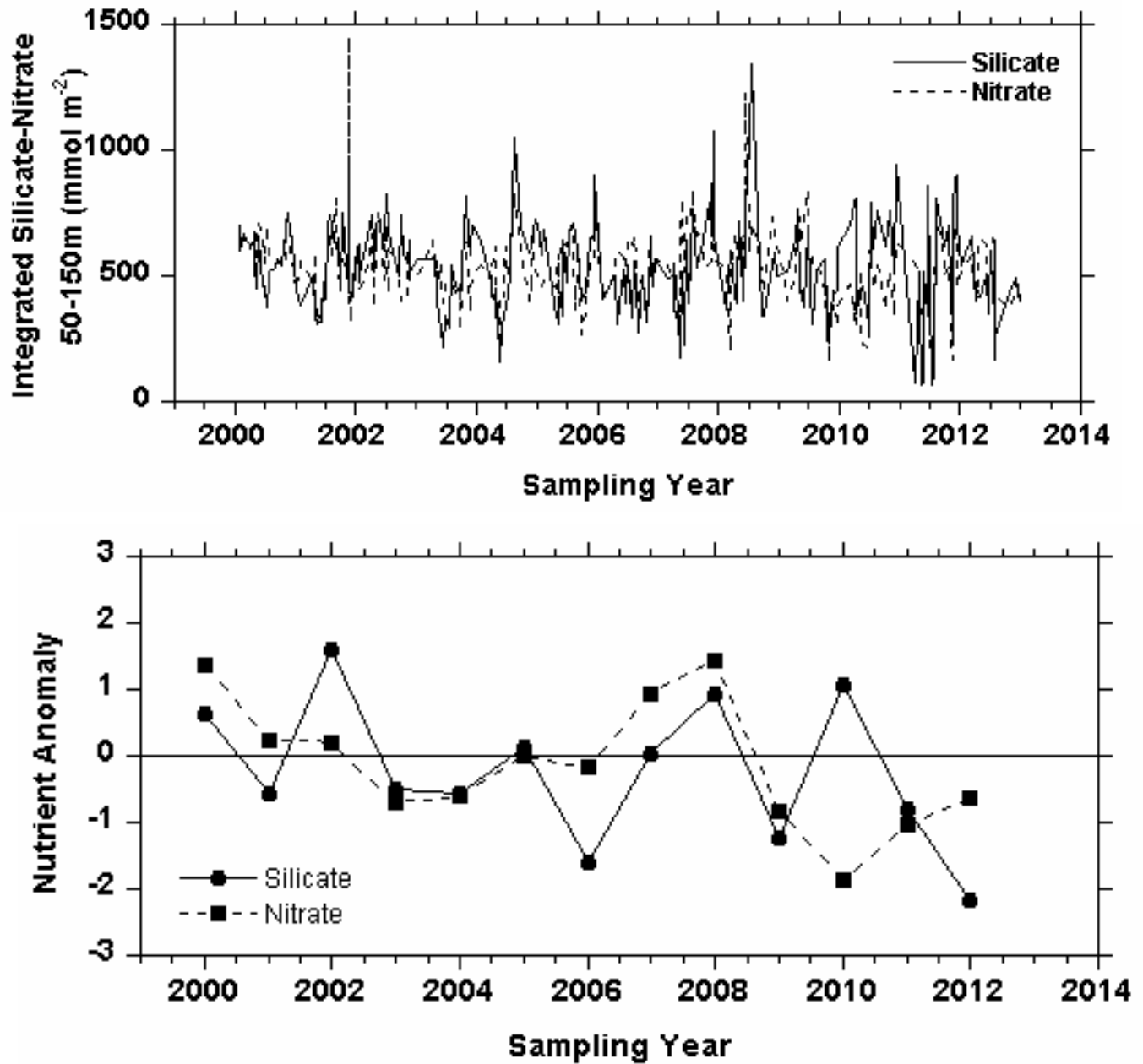


Figure 7. Time series of silicate and nitrate (50-150 m) inventories at S27, top panel. Bottom panel; least squares annual anomaly time-series of 50-150 m silicate and nitrate inventories at S27 (2000-10 reference period).

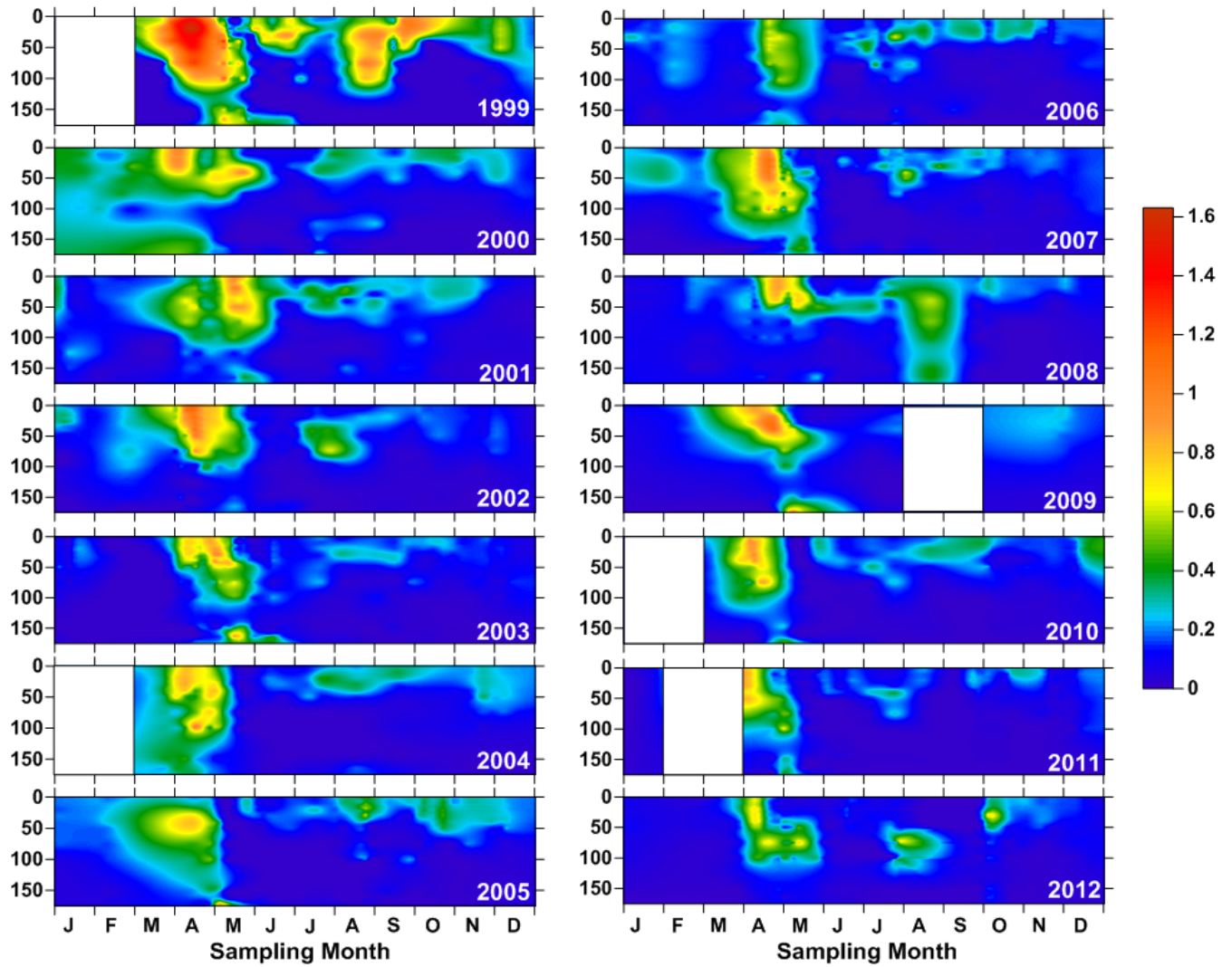


Figure 8. Time series of vertical chlorophyll a (log-transformed + 1) structure at S27 (coastal fixed station), 1999-2012. Sampling gaps > 2 consecutive months are blocked out in white.

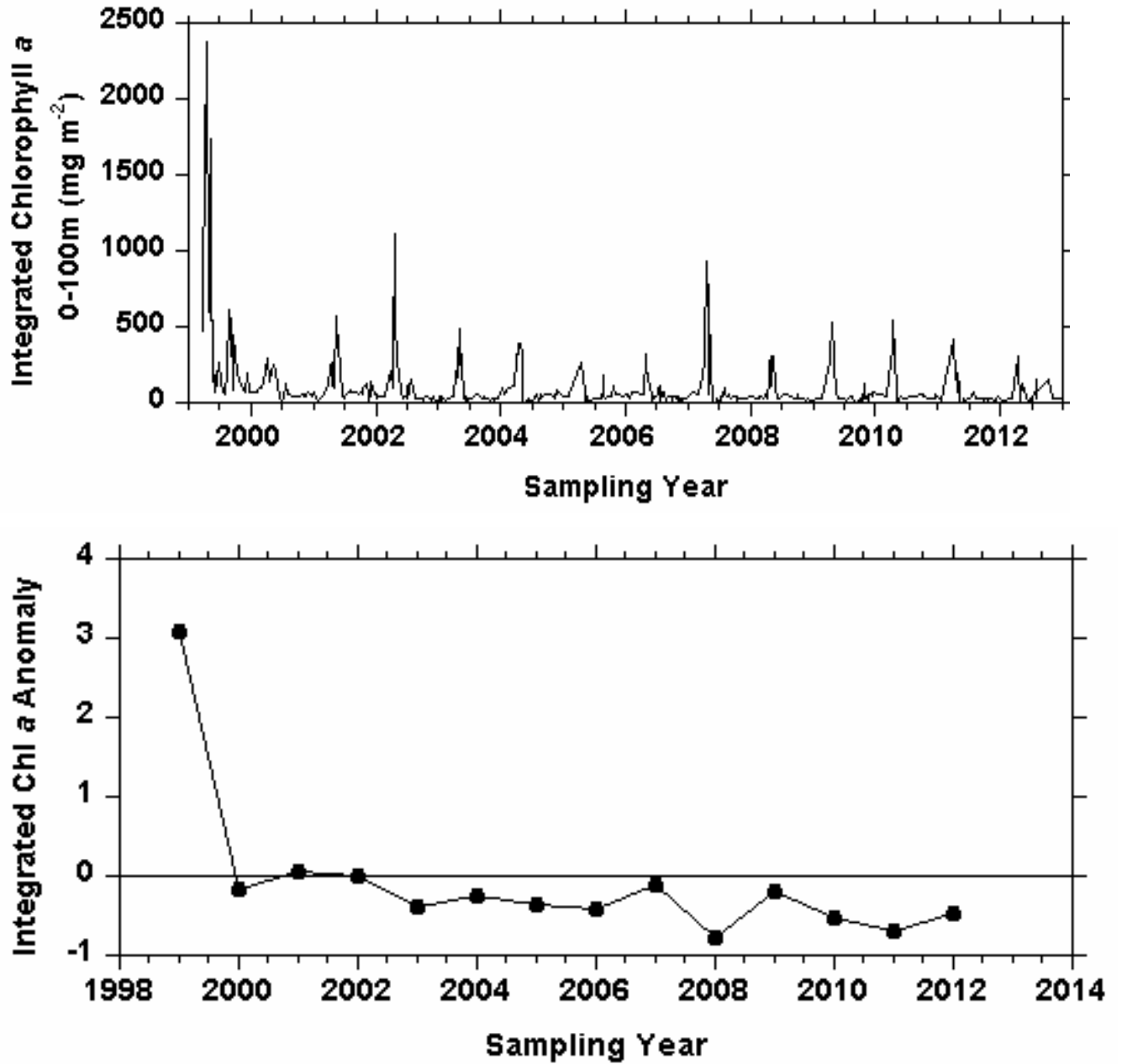


Figure 9. Time series of chlorophyll (0-100 m) inventories at S27, top panel. Bottom panel; least squares annual anomaly time-series of 0-100 m chlorophyll a inventories at S27 (1999-2010 reference period).

Silicate0-50m														
Location	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Seal Island (2J)	0.88	-0.30	-1.62	0.84		0.59	-0.65	-1.24	1.07	-0.45	-0.49	1.37	0.07	-1.10
Bonavista (3K)	0.81	-0.70	-0.53	1.60	1.36	-0.02	-0.57	-1.13	0.79	0.60	-1.38	-0.82	-0.34	-1.09
Station 27 (3L; fixed)	0.38	-1.50	-0.30	1.00	1.53	0.73	-0.37	0.13	1.13	-0.23	-1.15	-1.35	1.53	-1.40
Flemish Cap (3L, 3M)		-1.25	-1.07	-1.15	0.91	0.33	0.49	-0.41	0.70	0.40	-0.79	1.83	0.88	-2.03
SE Grand Banks (3LNO)	1.36	-1.15	-0.44	0.50	1.14	1.00	-0.25	-0.32	1.18	-1.30	-1.26	-0.46	-1.35	0.03
Silicate50-150m														
Location	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Seal Island (2J)	1.23	0.95	-0.68	0.45		-0.42	0.62	-1.84	1.32	-0.54	-0.95	-0.14	-1.33	-1.87
Bonavista (3K)	2.38	0.33	-0.05	0.86	0.01	-0.23	-0.20	-1.28	0.06	0.39	-1.04	-1.23	-1.63	-1.58
Station 27 (3L; fixed)	2.26	0.50	0.02	0.26	-0.12	-0.21	-0.25	-0.71	-0.05	1.04	-1.10	-1.63	-0.26	-1.86
Flemish Cap (3L, 3M)		0.65	-0.55	1.61	-0.51	-0.57	0.14	-1.60	0.03	0.94	-1.22	1.07	-0.79	-2.15
SE Grand Banks (3LNO)	2.31	-0.81	-0.11	0.66	0.22	1.08	-0.12	-0.49	-0.26	-0.72	-1.56	-0.21	-0.36	-0.08
Nitrate0-50m														
Location	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Seal Island (2J)	-0.31	-0.22	0.16	0.60		1.78	0.41	-1.57	0.80	-1.75	0.00	0.11	-0.25	-0.53
Bonavista (3K)	-0.38	-0.63	-0.46	1.39	1.71	0.44	-0.07	-1.25	1.29	-0.31	-0.42	-1.31	-0.20	-0.40
Station 27 (3L; fixed)	0.06	-1.03	0.11	1.15	2.04	0.64	-0.62	0.04	0.47	-0.66	-0.58	-1.62	1.66	-0.76
Flemish Cap (3L, 3M)		-0.08	1.77	-0.47	0.65	0.66	0.12	-0.82	0.67	0.18	-0.62	-2.06	-0.56	-1.47
SE Grand Banks (3LNO)	-0.13	-0.60	-0.16	0.26	2.48	0.80	-0.62	-1.06	0.77	0.03	-0.69	-1.08	-0.35	0.71
Nitrate50-150m														
Location	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Seal Island (2J)	0.61	0.48	0.21	0.26		0.76	0.37	0.27	1.29	-2.10	-0.83	-1.32	-0.47	-1.60
Bonavista (3K)	0.72	0.52	-1.05	-0.04	0.82	0.65	0.31	0.63	0.92	-0.44	-0.54	-2.49	-1.53	-1.10
Station 27 (3L; fixed)	1.34	0.35	-0.66	-0.51	0.70	0.25	-0.20	1.74	0.15	-0.32	-0.83	-2.00	0.84	-1.34
Flemish Cap (3L, 3M)		1.56	0.36	0.34	-0.60	-0.47	0.13	-0.05	1.08	1.63	-0.73	-1.80	-0.93	-0.52
SE Grand Banks (3LNO)	0.17	-1.56	-1.05	0.73	0.69	1.64	-0.69	0.99	0.17	0.31	-1.47	0.05	0.27	0.52
Chlorophyll a (0-100m)														
Location	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Seal Island (2J)		0.66	1.91	0.72	-1.00	-0.36	0.26	0.70	-1.27	-1.21	0.33	-0.73	-1.51	-1.43
Bonavista (3K)		0.56	0.02	-1.77	-1.46	0.78	-0.05	0.53	1.16	-1.01	1.06	0.20	2.39	-1.59
Station 27 (3L; fixed)	3.10	-0.19	-0.12	0.11	-0.35	-0.28	-0.47	-0.43	-0.09	-0.65	-0.09	-0.54	-0.76	-0.96
Flemish Cap (3L, 3M)		0.34	-0.09	-1.01	-2.00	0.08	1.48	-0.51	0.56	-0.40	1.37	0.17	-3.76	-1.72
SE Grand Banks (3LNO)		-1.50	0.79	0.04	-0.98	0.02	1.06	-0.46	1.18	-1.29	1.32	-0.18	-2.58	-1.16

Figure 10. Annual scorecard anomalies of shallow (0-50 m) and deep (50-150 m) nutrient inventories (silicate and nitrate) and chlorophyll a (0-100 m) across the different ocean sections and fixed station (S27). The reference period used to compute annual anomalies was 1999 to 2010.

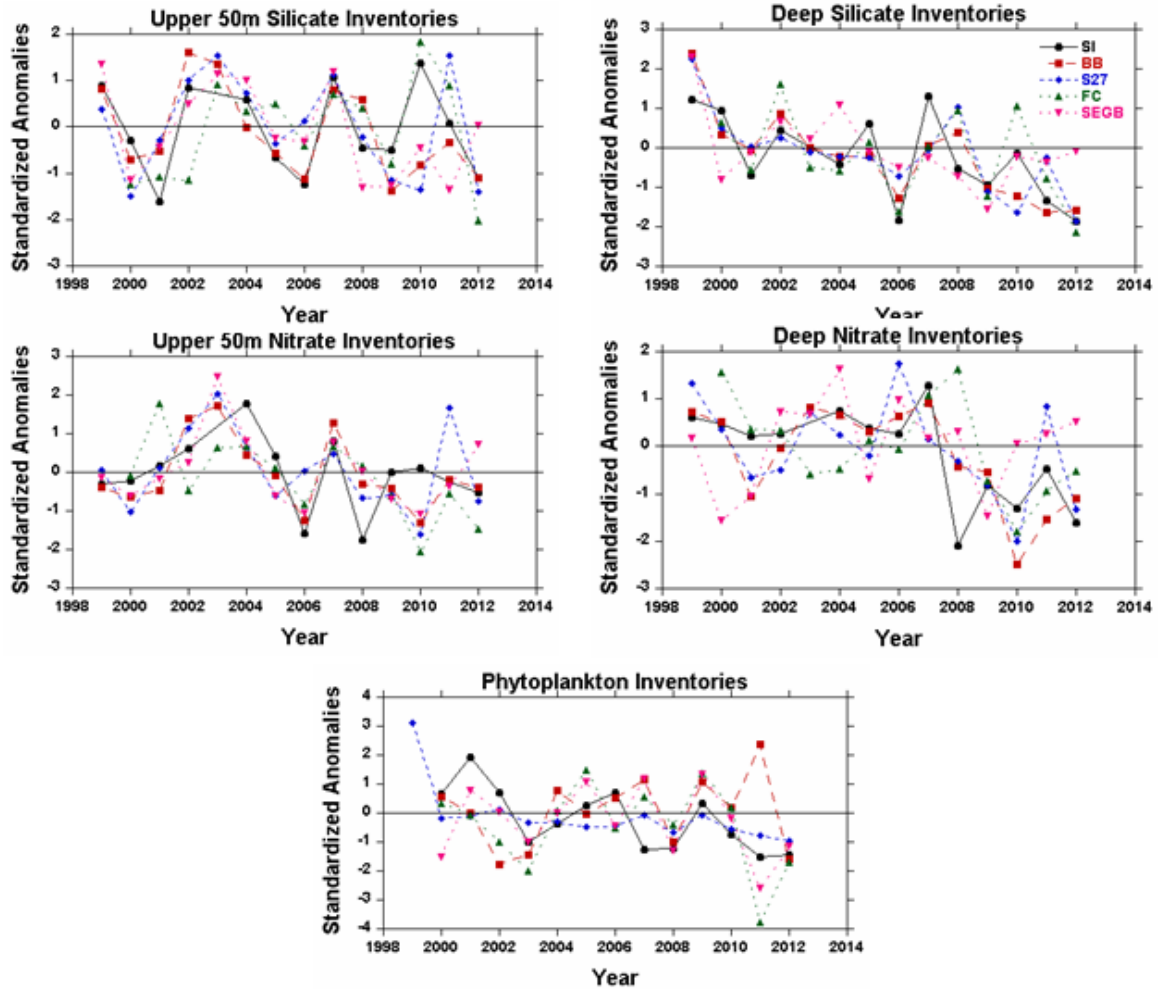


Figure 11. Time series plots of standardized annual anomalies of shallow (0-50 m) and deep (50-100 m) nutrient (silicate in left panels and nitrate in right panels) inventories and phytoplankton biomass (bottom centre panel) along the standard sections (SI = Seal Island; BB=Bonavista; S27=Station 27; FC=Flemish Cap; SEGB=southeast Grand Bank). The reference period used to compute anomalies was 1999-2010. The legend identifying each section is provided in upper right panel.

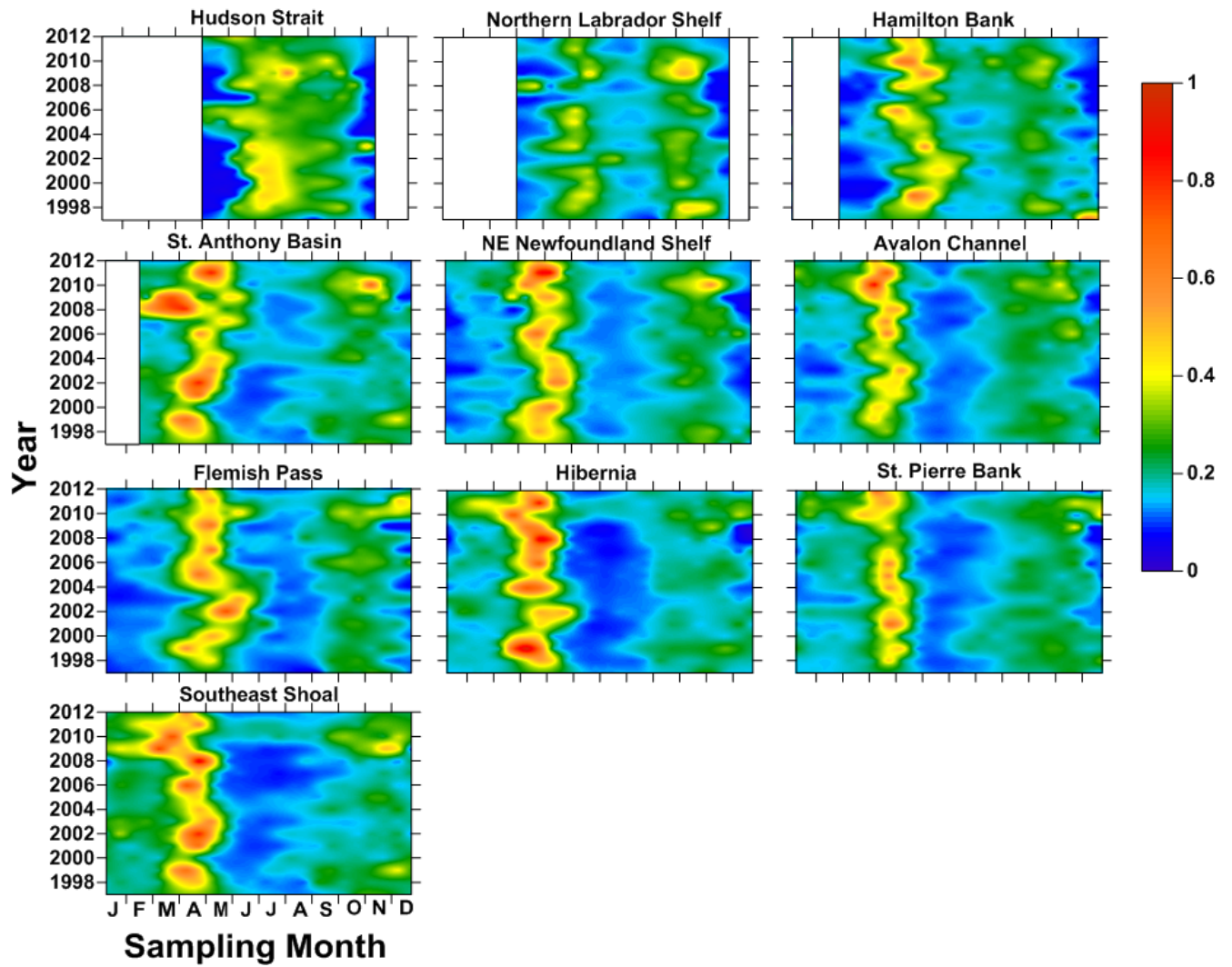


Figure 12. Time-series of surface chlorophyll a concentrations (log-transformed + 1;  $\text{mg m}^{-3}$ ), from merged bi-weekly SeaWiFS-MODIS ocean colour data along statistical sub-regions across the Newfoundland and Labrador area during 1998-2012. See Figure 2 for locations of statistical sub-regions in Newfoundland and Labrador area. Normal ice-covered periods are blocked out in white.

<b>Magnitude of Spring Bloom</b>															
Location	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Hudson Strait	-0.81	0.38	-0.65	0.24	0.39	-0.62	0.92	0.84	2.46	-0.87	0.97	-0.41	-1.09	-0.91	-0.84
Northern Labrador Shelf	0.13	0.04	-0.52	0.77	-0.98	0.78	-0.68	-0.01	0.34	-0.74	2.95	0.08	-1.03	-0.54	-0.60
Hamilton Bank	-0.28	1.13	-1.11	1.06	-0.72	-0.66	-1.06	-0.21	1.14	-1.45	0.70	1.22	1.30	-1.03	-0.03
St. Anthony Basin	-0.15	0.32	-0.75	0.05	0.73	-1.71	-0.36	-0.61	-0.13	-0.48	2.83	0.36	-0.49	0.77	-0.37
NE Newfoundland Shelf	-0.18	0.00	0.33	-1.20	-0.14	-0.37	-0.74	-0.78	1.16	-0.05	-0.75	1.60	-0.35	2.38	-0.91
Avalon Channel	-1.56	-0.71	-0.65	-0.27	0.26	-0.15	-0.40	-0.78	0.22	0.42	-0.16	1.41	2.51	0.70	-0.81
Hibernia	-0.48	2.27	-0.65	-0.89	-0.08	-1.29	1.03	-1.04	-0.06	-0.05	1.50	0.72	-0.26	0.13	-0.85
Flemish Pass	-1.26	-0.16	0.11	-0.97	2.01	-0.41	0.23	0.77	-0.18	-0.03	-0.95	1.52	1.17	-1.29	-0.58
St. Pierre Bank	-1.03	-0.46	-1.42	1.58	-0.53	-0.74	-0.17	0.05	0.32	-0.37	-1.20	1.88	0.53	0.24	1.33
SE Shoal	-0.36	0.56	-1.56	0.03	1.38	-0.55	-0.82	-1.00	-0.12	-0.78	2.03	1.13	0.27	0.65	-0.86
<b>Peak Timing of Spring Bloom</b>															
Location	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Hudson Strait	-0.51	0.84	0.80	0.18	0.94	-0.46	0.05	-1.16	-0.44	0.42	-0.71	2.15	0.19	-0.19	-2.09
Northern Labrador Shelf	-0.38	-0.06	0.19	-0.40	0.89	-0.66	-0.23	-0.39	-0.47	3.09	-1.45	0.37	0.10	-0.38	-0.23
Hamilton Bank	-0.50	-0.12	1.23	0.86	1.86	0.43	-0.07	-0.48	-1.78	0.91	-1.15	0.80	-0.97	-0.20	-0.82
St. Anthony Basin	-0.34	-0.84	-1.24	-0.03	0.14	0.94	0.71	0.00	-0.20	0.27	-1.26	-1.92	1.31	1.03	1.43
NE Newfoundland Shelf	-0.38	-1.23	0.20	1.49	1.41	1.34	0.73	-0.86	-1.06	0.40	0.60	-0.35	-1.67	0.05	-0.69
Avalon Channel	0.02	-1.23	-0.52	1.17	0.45	2.33	-0.15	-0.97	0.39	0.03	1.13	-0.87	-1.28	0.14	-0.64
Hibernia	0.78	-0.96	-0.73	0.92	1.88	0.10	-0.32	0.22	0.13	0.16	1.04	-0.79	-2.30	0.37	-0.48
Flemish Pass	-0.27	-1.73	0.25	1.25	1.19	2.12	0.20	-0.78	-1.39	-0.18	-0.20	-0.31	0.52	-0.09	-0.59
St. Pierre Bank	0.02	1.08	-0.20	0.57	0.38	1.43	0.45	-0.71	0.13	-0.05	0.75	0.37	-2.74	-0.43	-1.06
SE Shoal	0.22	-0.37	-0.83	0.59	0.78	1.73	0.85	0.05	0.13	0.77	0.66	-2.13	-1.53	-0.67	-0.25
<b>Duration of Spring Bloom</b>															
Location	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Hudson Strait	-0.32	-0.04	-0.62	-0.25	0.57	-0.47	1.58	0.68	2.44	-1.21	0.02	-0.95	-0.37	0.16	-1.22
Northern Labrador Shelf	0.47	-0.20	-0.53	1.47	-0.88	0.77	-0.40	-0.76	0.51	-0.04	2.50	-1.28	-0.72	-0.69	-0.21
Hamilton Bank	0.86	-0.87	0.57	2.20	1.06	-1.27	0.42	0.77	-0.15	-0.64	-1.41	0.38	-0.60	-0.85	-0.47
St. Anthony Basin	0.62	0.19	-0.81	-0.36	-0.11	-2.85	0.45	0.52	0.13	-0.41	1.89	0.14	0.26	-0.23	0.58
NE Newfoundland Shelf	0.70	1.55	0.40	-0.36	-0.87	-0.14	-0.15	-0.97	-0.67	0.56	0.03	2.47	-1.04	-0.92	-0.56
Avalon Channel	-0.11	0.30	-0.04	1.45	1.70	-0.36	0.93	1.69	-0.72	-0.99	-0.44	-0.41	-0.80	-0.90	-1.32
Hibernia	0.56	0.06	1.00	0.21	2.22	0.46	1.34	-0.39	-0.89	-0.64	-0.97	0.13	-1.10	-1.33	-0.67
Flemish Pass	-0.18	-0.26	0.17	1.38	-0.49	-0.26	1.49	-0.41	-0.28	-0.81	-0.83	0.00	2.43	-0.86	-1.09
St. Pierre Bank	-0.58	-0.99	-0.51	-0.28	0.44	-0.51	0.20	-1.38	-0.55	-0.05	0.98	1.99	1.80	0.52	-1.09
SE Shoal	0.74	0.23	-0.93	-0.41	-0.11	-0.39	-0.03	0.39	-1.20	-0.69	-0.16	0.83	-0.55	2.95	-0.66

Figure 13. Annual scorecard anomalies of spring bloom indices for overall magnitude of the spring bloom (integrated chlorophyll a concentration), peak timing and duration of the spring bloom across the Newfoundland and Labrador statistical sub-regions during 1998-2012. The reference period used to compute annual anomalies was 1998-2010.

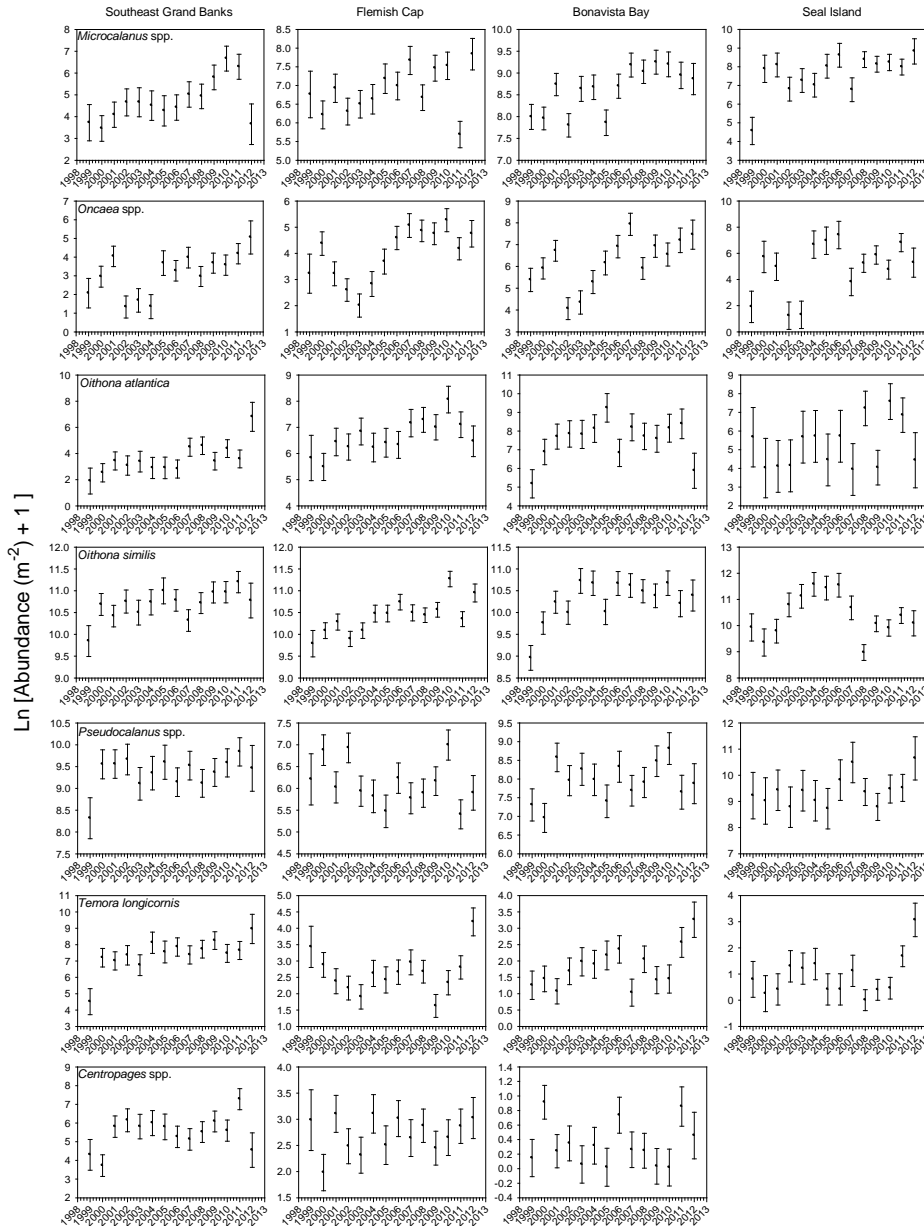


Figure 14. Seasonally-adjusted estimate of the mean abundance of small copepods from the oceanographic sections for the period 1999-2012. The error bars represent standard errors. Values from the Southeast Grand Banks are based on two occupations per year (spring, fall); values from the Flemish Cap and Bonavista sections are based on three occupations per year (spring, summer, fall); values from the Seal Island sections are based on one occupation per year (summer). The Southeast Grand Banks and Flemish Cap sections are in the southern ecoregion, while the Bonavista Bay and Seal Island sections are in the northern ecoregion.



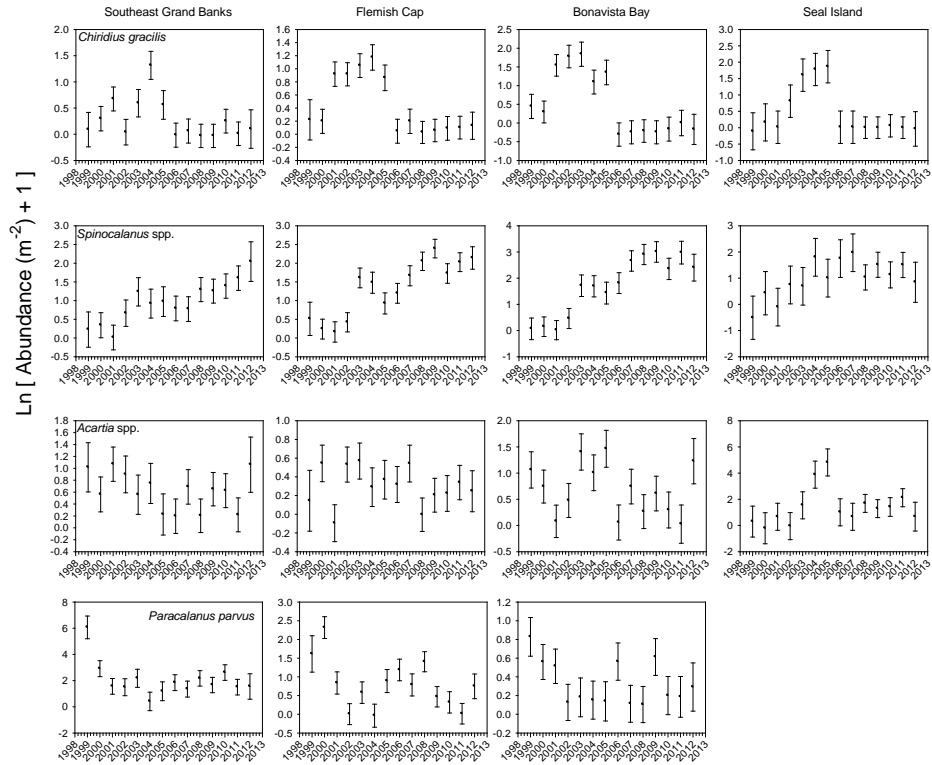


Figure 14. (Cont'd.)

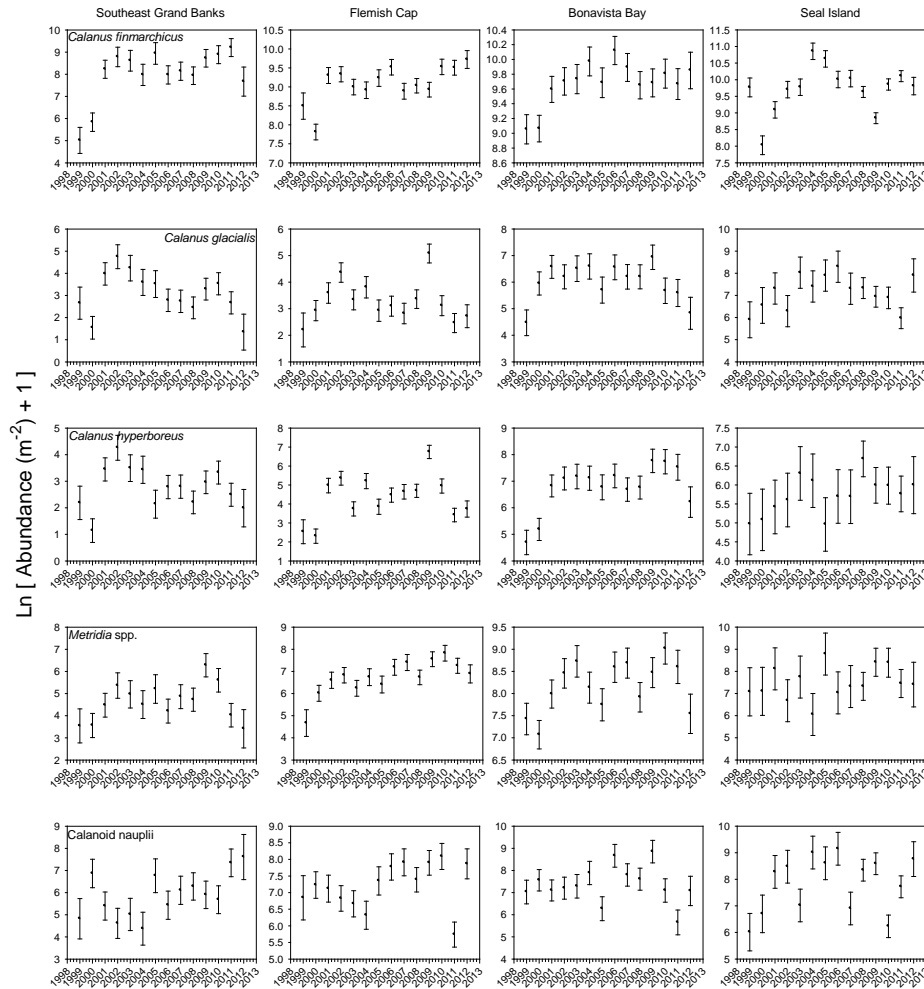


Figure 15. Seasonally-adjusted estimate of the mean abundance of large copepods from the oceanographic sections for the period 1999-2011. The error bars represent standard errors. Values from the Southeast Grand Banks are based on two occupations per year (spring, autumn); values from the Flemish Cap and Bonavista sections are based on three occupations per year (spring, summer, fall); values from the Seal Island section are based on one occupation per year (summer). The Southeast Grand Banks and Flemish Cap sections are in the southern ecoregion, while the Bonavista Bay and Seal Island sections are in the northern ecoregion.

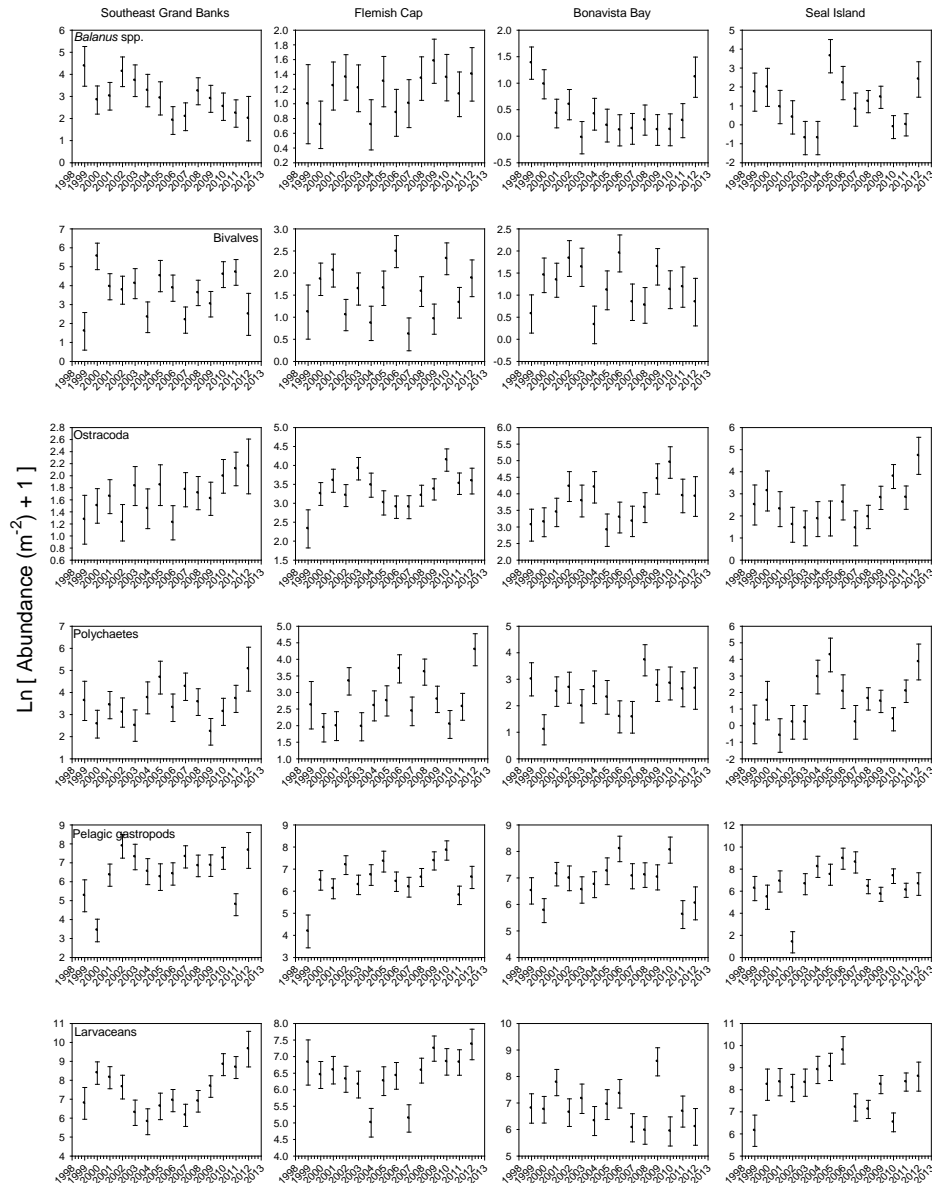


Figure 16. Seasonally-adjusted estimate of the mean abundance of meroplankton and other selected taxa from the oceanographic sections for the period 1999-2011. The error bars represent standard errors. Values from the Southeast Grand Banks are based on two occupations per year (spring, fall); values from the Flemish Cap and Bonavista sections are based on three occupations per year (spring, summer, fall); values from the Seal Island section are based on one occupation per year (summer). The Southeast Grand Banks and Flemish Cap sections are in the southern ecoregion, while the Bonavista Bay and Seal Island sections are in the northern ecoregion.

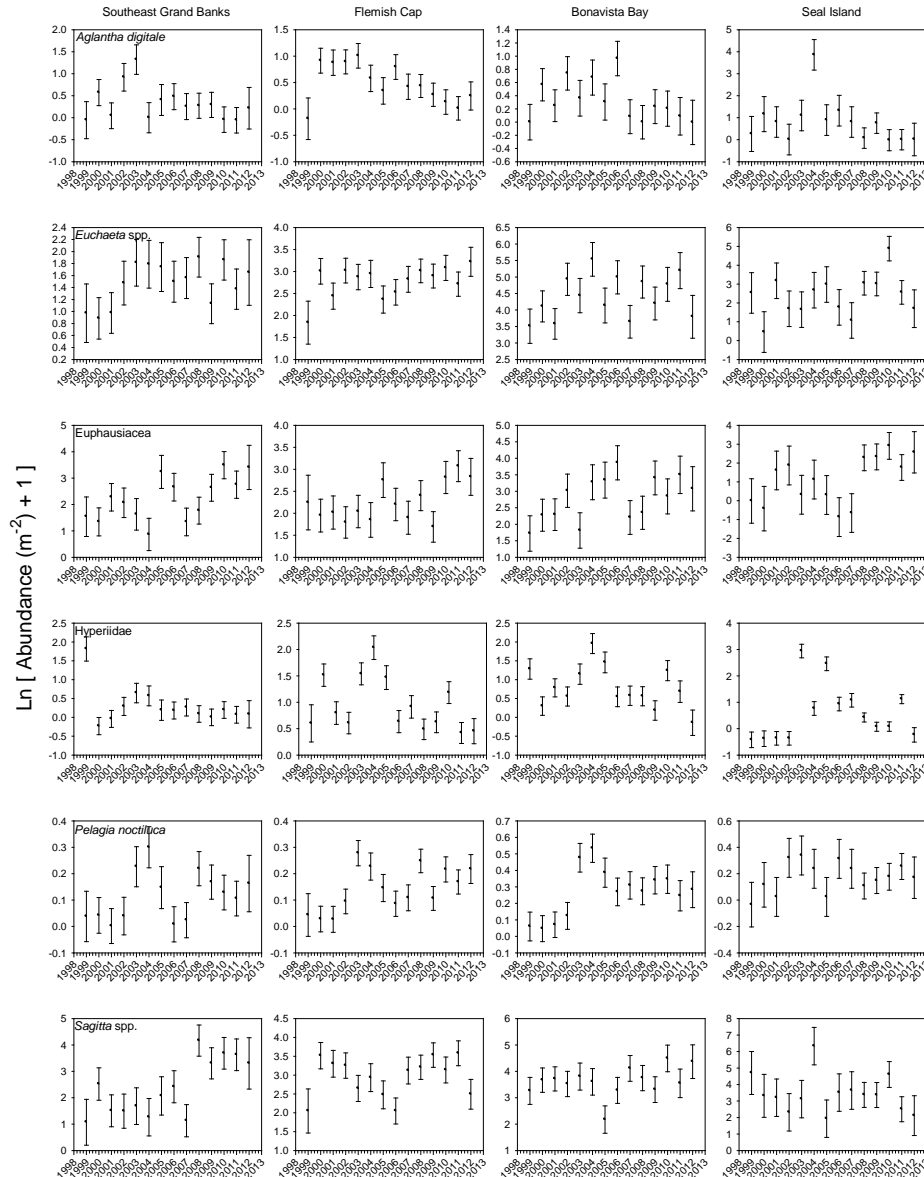


Figure 17. Seasonally-adjusted estimate of the mean abundance of carnivorous zooplankton from the oceanographic sections for the period 1999-2010. The error bars represent standard errors. Values from the Southeast Grand Banks are based on two occupations per year (spring, fall); values from the Flemish Cap and Bonavista sections are based on three occupations per year (spring, summer, fall); values from the Seal Island section are based on one occupation per year (summer). The Southeast Grand Banks and Flemish Cap sections are in the southern ecoregion, while the Bonavista Bay and Seal Island sections are in the northern ecoregion.

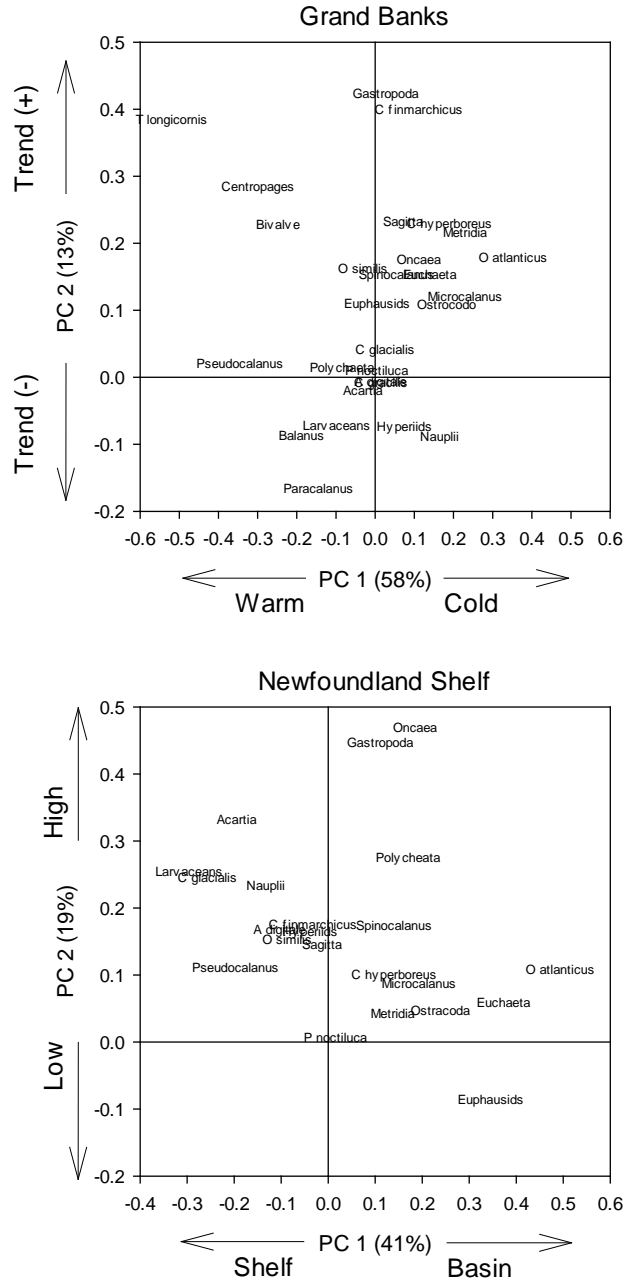


Figure 18. Principal component scores of taxa from the Grand Banks (southern ecoregion—top panel) and Newfoundland Shelf (northern ecoregion—bottom panel) based on the analysis of the variance-covariance matrix of mean annual log-transformed abundance estimates. Legends along each axis are provided to give an indication of explanatory variables that appear to be most closely associated with the variations along each axis.

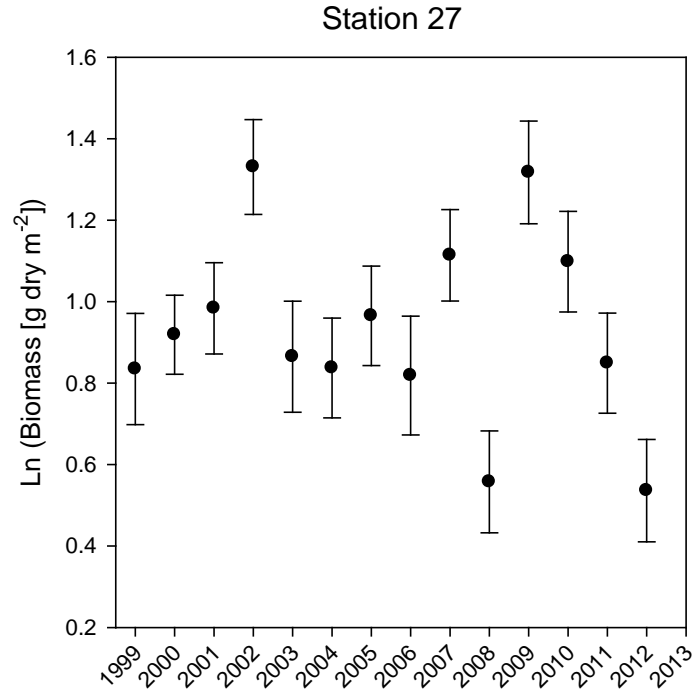


Figure 19. Seasonally-adjusted estimates of the mean biomass of 8 dominant copepod species from Station 27 for the period 1999-2010. The error bars represent standard errors.

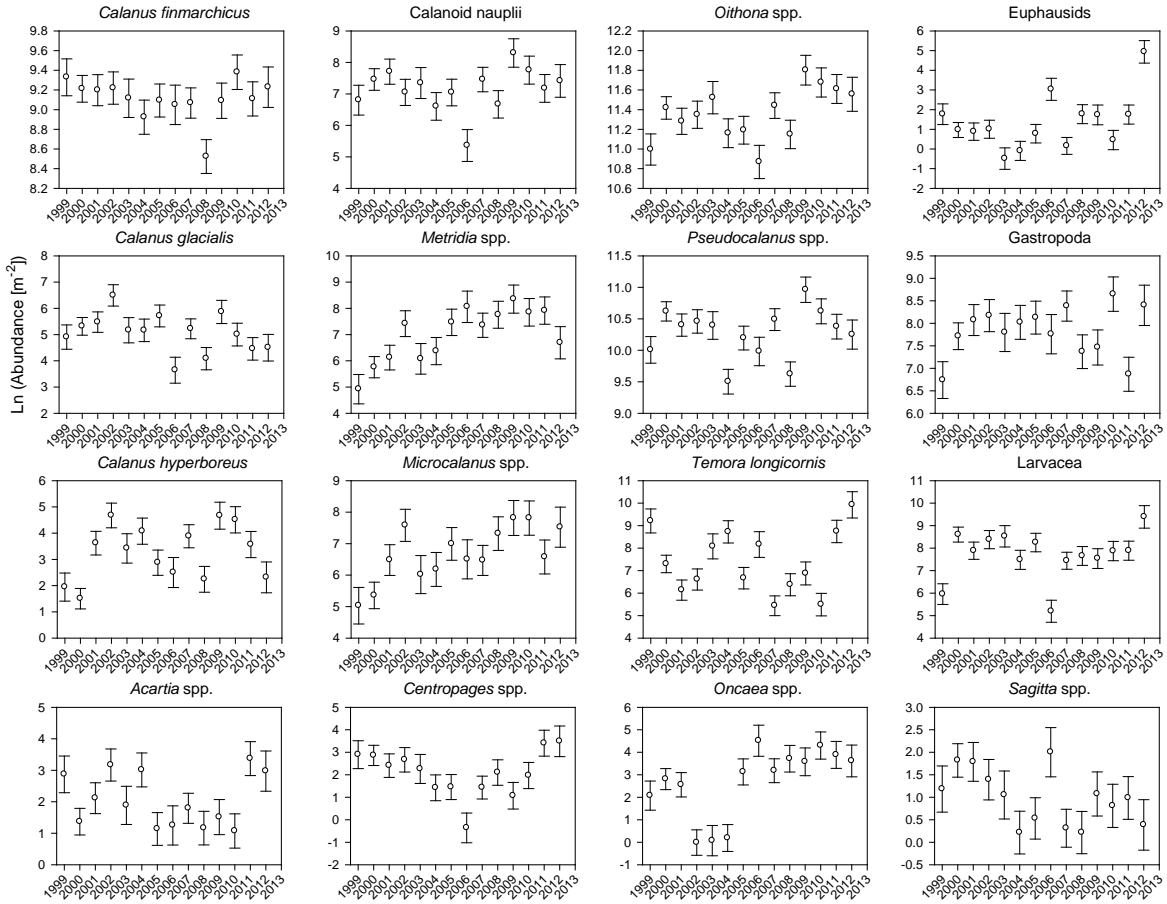


Figure 20. Seasonally-adjusted estimate of the mean abundance of twelve dominant zooplankton taxa from Station 27 for the period 1999-2010. The error bars represent standard errors.

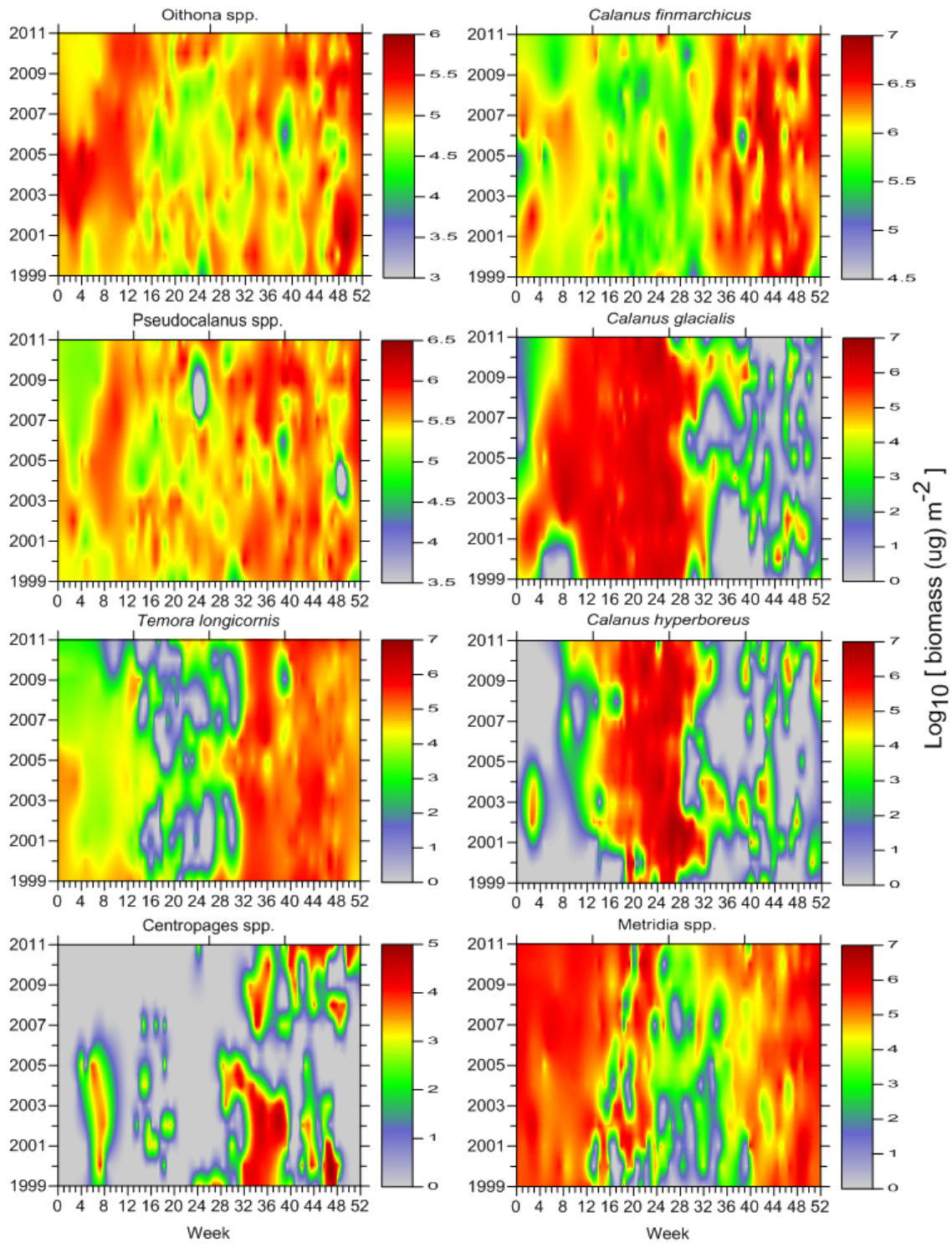


Figure 21. Contour diagram of total biomass of eight dominant copepod species from S27. Biomass is plotted on a logarithmic scale.



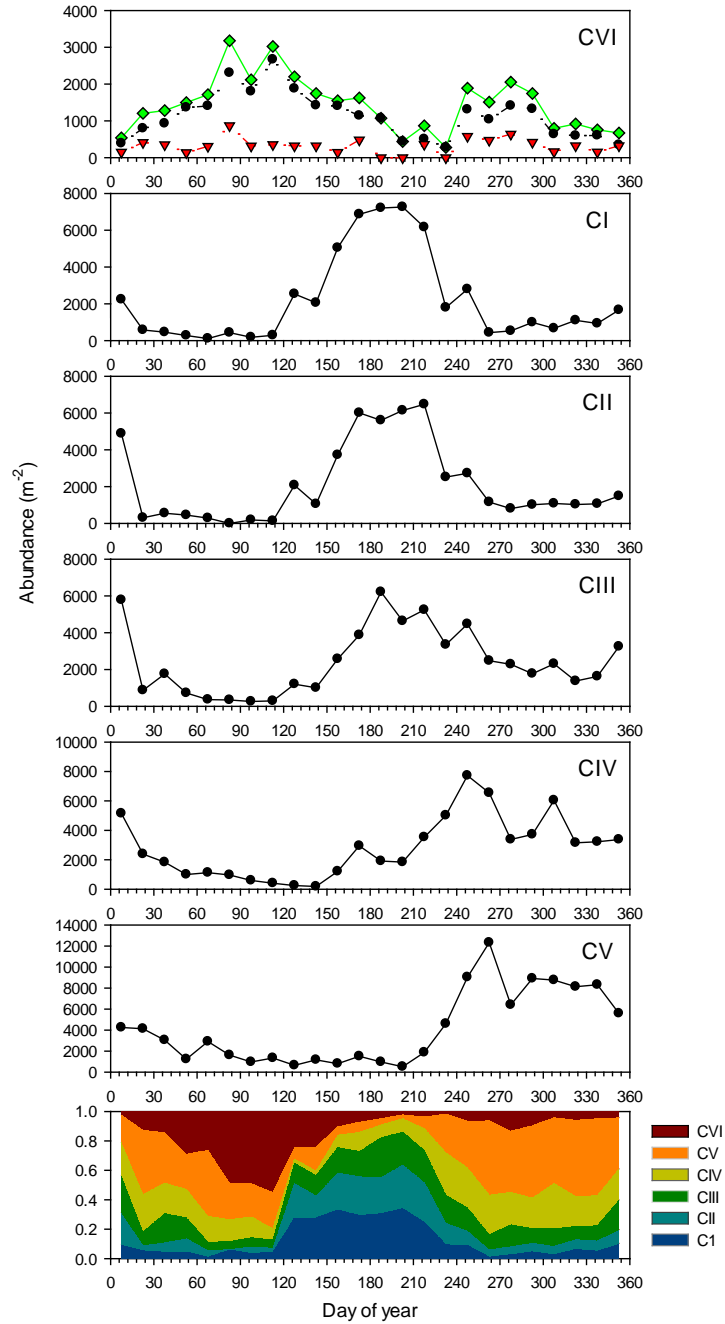


Figure 22. Climatological (2000-10) seasonal cycle in the abundance of adult (CVI; total-diamonds; females-black circles; males-inverted triangles) and copepodite stages (CI-CV) at S27. The bottom panel represents the relative stage composition.

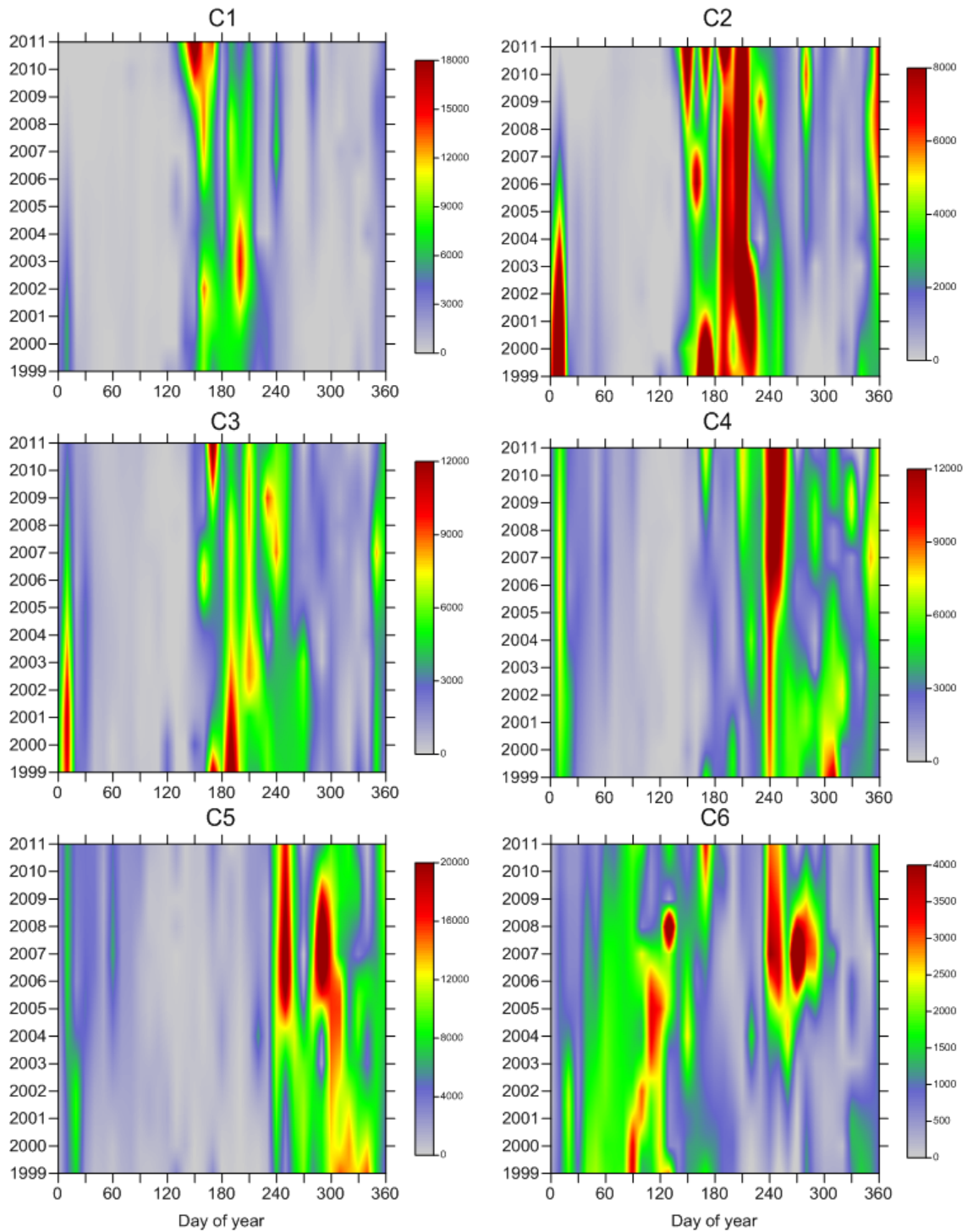


Figure 23. Seasonal cycle of abundance (number  $m^{-2}$ ) of stage CI to CVI copepodites of *Calanus finmarchicus* for the period 1999-2011.

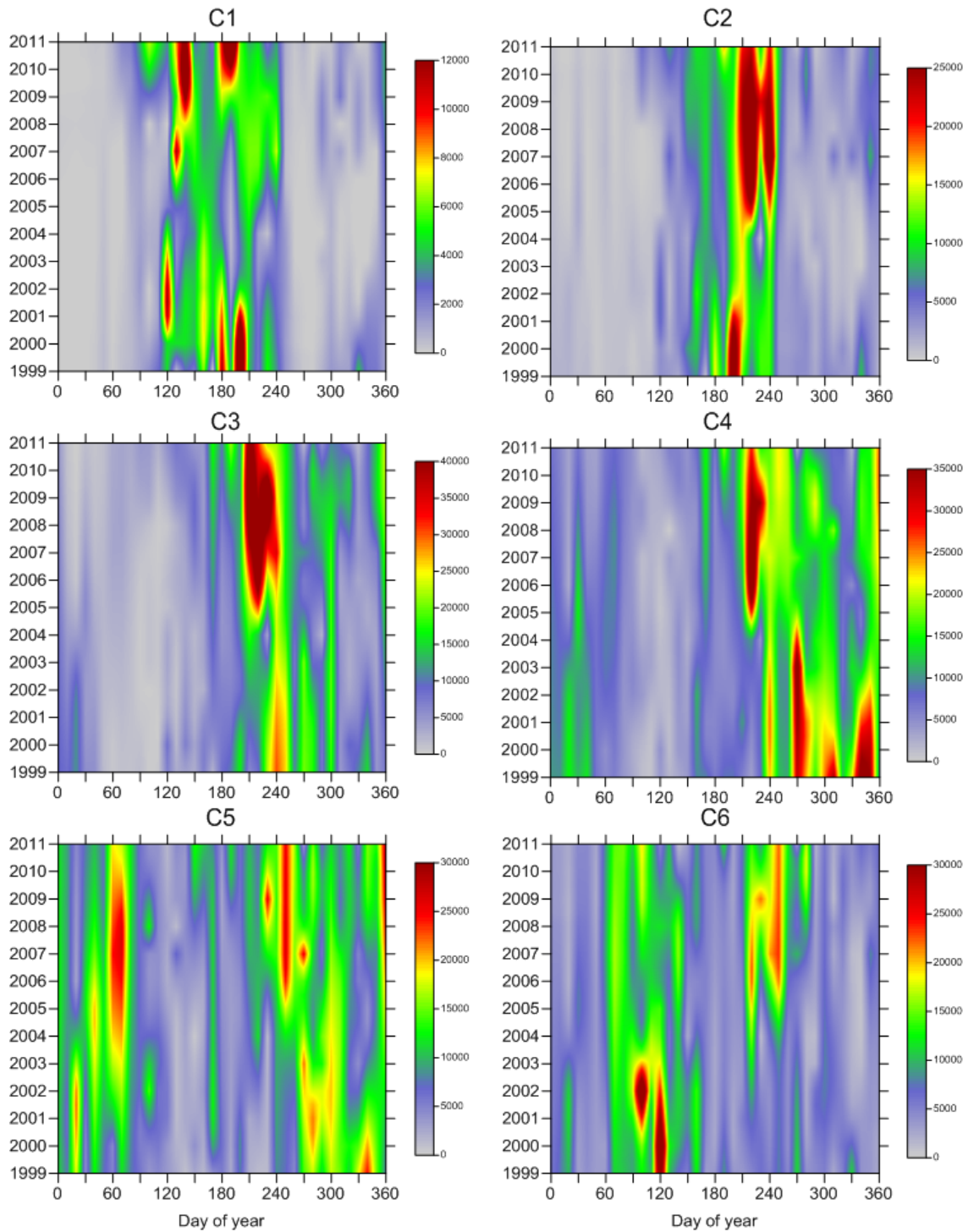


Figure 24. Seasonal cycle of abundance (number  $m^{-2}$ ) of stage C1 to CVI copepodites of *Pseudocalanus* spp. for the period 1999-2011.