Fisheries and Oceans Canada Pêches et Océans Canada
Science Sciences

C S A S *S C C S*

Canadian Science Advisory Secretariat **Secrétariat canadien de consultation scientifique**

Research Document 2011/074 **Document de recherche 2011/074**

Newfoundland & Labrador Region **Région de Terre-Neuve et Labrador**

Optical, chemical, and biological oceanographic conditions on the Newfoundland and Labrador Shelf during 2009 and 2010

Propriétés optiques, chimiques et biologiques de l’océan sur le plateau Terre-Neuvien au cours des années 2009 et 2010

P. Pepin, G. Maillet, S. Fraser, T. Shears, and G. Redmond

Fisheries sand Oceans Canada
Science Branch
PO Box 5667
St. John’s NL A1C 5X1

ISSN 1499-3848 (Printed / Imprimé)
ISSN 1919-5044 (Online / En ligne)

Canada

Correct citation for this publication:

Pepin, P., Maillet, G., Fraser, S., Shears, T., and Redmond, G. 2011. Optical, chemical, and biological oceanographic conditions on the Newfoundland and Labrador Shelf during 2009 and 2010. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/074. iv + 45 p.

ABSTRACT

We review seasonal and interannual variations in the concentrations of major nutrients, chlorophyll *a*, as well as the abundance of major taxa of zooplankton measured from Station 27 and along standard transects of the Atlantic Zone Monitoring Program (AZMP) in the Newfoundland region for 2009 and 2010. Across the region, annual nitrate inventories (shallow and deep) have declined since 2008 and appear to be continuing to decrease in 2010. Chlorophyll concentrations in 2009 were at their highest levels since the start of AZMP activities in the region but returned to near normal values in 2010. In 2009 and 2010, the principal zooplankton indices indicated that abundance was generally higher than average, with densities reaching their highest levels in 2010 along many of the oceanographic sections. The indices of inventories and abundances across trophic levels (nutrients, phytoplankton and zooplankton) generally exhibit weak associations (i.e., correlations) between adjacent trophic levels. There was no single physical environmental variable that demonstrated a widely consistent pattern of correlation with either nutrient inventories, phytoplankton abundance or with the wide diversity of zooplankton taxa. This may be the result that over the last decade the physical environment of the Newfoundland Shelf showed the lowest overall variability relative to previous decades going back to 1950.

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 des principales espèces du zooplancton et du phytoplancton, récoltées à la station 27 et le long de sections normalisés du Programme de monitorage de la zone atlantique (PMZA) dans la région de Terre-Neuve en 2009 et 2010. Dans toute la région, les inventaires de nitrate, ont diminués depuis 2008 et le déclin semble continuer en 2010. L'abondance du phytoplancton en 2009 a atteint la plus haute concentration observée depuis le début du PZMA mais était semblable à la moyenne en 2010. En 2009 et 2010, les indices d'abondance des principaux zooplanctons étaient généralement plus hauts que la moyenne, avec des densités atteignant les niveaux les plus élevés dans une grande partie de la région. Les indices d'inventaire et d'abondance parmi les divers niveaux trophiques (éléments nutritifs, phytoplancton, zooplancton) démontraient généralement de faibles associations (c.à.d. corrélations) entre niveaux adjacents. Aucun indice de l'environnement physique n'à démontrer un patron de corrélation uniforme ou conforme soit avec les inventaires d'éléments nutritifs, d'abondance de phytoplancton ou avec une grande diversité d'espèces de zooplancton. Ces patrons sont possiblement le résultat de la faible variabilité des conditions physique de l'environnement du plateau continental de Terre-Neuve et du Labrador au cours de la dernière décennie relativement aux périodes antérieurs allant jusqu'à 1950.

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 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 2002). Non-standard measurements or derived variables are described.

SAMPLE COLLECTION

Three seasonal oceanographic surveys were conducted in the Newfoundland and Labrador Region during the 2010 calendar year, in addition to repeat day-trips to the fixed coastal station (S27). A total of 384 stations were sampled across the fixed station and all oceanographic sections in 2010 (Fig. 1; Table 1). No occupations of S27 were achieved during January-February 2010 owing to the availability of resources (platforms) and, to some extent, difficulties with weather and equipment failure.

Increased atmospheric levels of carbon dioxide are hypothesized to be responsible for recent trends in acidification detected in the world oceans (Caldeira and Wickett 2003). Increasing acidity in the ocean will decrease the degree of saturation of carbonates (calcite and aragonite) thereby altering basic ocean chemistry and potentially influencing the marine organisms which utilize this mineral in their chemical structures. Some examples of marine organisms include crustaceans, gastropoda, and bivalvia which are important to higher trophic levels in the marine food chain (Fabry et al. 2008, Reis et al. 2009). High resolution profile measurements have begun in the Newfoundland and Labrador Region to monitor trends in ocean pH during seasonal oceanographic surveys. We monitored pH using an in-situ sensor (Seabird SBE-18) interfaced with our SBE 911 CTD during summer and autumn 2010 missions along all oceanographic sections to a maximum depth of 1200 m (Table 1).

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$_z$ (sigma-t)). The stratification index (SI) was calculated as:

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

where sig-t $_{50}$ and sig-t $_{zmin}$ are interpolated values of sigma-t for the depths of 50 m and z_{min} (the minimum depth of reliable CTD data); typically z is around 5 m and always less then 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_d), which is determined by dissolved and coloured substances and particulate matter in seawater. The vertical attenuation coefficient (K_d) was 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:

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

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.

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 inventories, 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. Physical variables, inventories of nutrients and chlorophyll were not transformed. To derive an estimate of the interannual 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 because they have not yet been fully inter-calibrated 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 Latitude 42-71°W Longitude) are routinely produced from SeaWiFS/MODIS data[1]. 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. 2).

OBSERVATIONS

MIXED-LAYER AND STRATIFICATION INDEX

We were unable to track the early seasonal development of the mixed-layer and upper water-column stratification at S27 in 2010 given the lack of observations during winter. Relatively large variability in the mixed-layer depths occurred during spring and early summer compared to average conditions in previous years (1999-2009) (Fig. 3). The onset of deepening of the mixed-layer that normally begins in the early autumn was delayed considerably by ca. 1 month, in contrast to average conditions. The seasonal development of stratification at S27 was also delayed compared to earlier years. In 2010, maximum stratification was observed in September compared to August for the 1999-2010 average.

OPTICAL PROPERTIES

The seasonal development of optical properties at S27 was consistent with observations in previous years with the exception of the spring bloom period in April (Fig. 4). Overall, euphotic depths during spring 2010 reached ~10 m compared to the normal range of 30 m, and correspondingly the maximum vertical light attenuation was about two-fold greater. As a result of higher light attenuation levels observed in spring, euphotic depths were generally shallow indicating a more intense phytoplankton bloom but quickly deepened following the spring bloom and approached depths in excess of 100 m by early May. We suggest some caution in the overall interpretation of any given time-series because sampling may not capture

---

[1] (http://www2.mar.dfo-mpo.gc.ca/science/ocean/ias/seawifs/seawifs_1.html)

the full dynamic range of the variables because the occupations of S27 can vary from year to year, particularly during winter and spring.

NUTRIENTS

The vertical distributions of the 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 is most often associated with limiting the growth of phytoplankton and supported by our *in-situ* observations, more emphasis in this report will be placed on variability in nitrate concentrations. The time-series of 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. 5). 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 rapidly in the upper 50 m to <1.0 mmol m^{-3} by early April and remained relatively low throughout the summer. Periodic intrusions of nitrate from depth that have been observed during earlier years were limited in near-surface waters in 2010. The seasonal evolution of vertical nitrate structure at S27 was different compared to previous years with the largest observed reduction in the time-series along with greatly reduced nutrient replenishment during the late autumn. Deep water concentrations of nitrate shoaled only briefly during early autumn, coincident with the annual minima in water column salinity from ice-melt further north. 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.

The inventories of nutrients are strongly influenced by seasonal biological processes operating throughout the upper water-column. The inventory of nitrate at S27 within the upper 50 m was the lowest observed since the start of the time-series (Fig. 6). The annual mean inventories have decreased by 50 %, from ~100 mmol m^{-2} in 2000 to 50 mmol m^{-2} in 2010. The annual mean inventory in 2010 fell below the overall long-term average (66 mmol m^{-2}) for the first time in contrast to previous years which remained at or above this level (Fig. 6). The absolute monthly inventory anomalies were consistently negative for almost all sampling months in 2010 (Fig. 6). This pattern was different in earlier years, with both short-term positive and negative monthly anomalies which may be indicative of a relatively stable pattern in nutrient recycling at S27 (Fig. 6). Most of the nitrate in the upper water column in 2010 was consumed during the spring bloom suggestive of an intense production cycle compared to previous years, although the overall amount available at the start of the year was less than in previous years. The deep (50-150 m) inventories of nitrate at S27 showed a downward trend in 2010, similar to that observed in surface waters, relative to earlier years. The deep inventory in 2010 was at the lowest level observed since the start of the program (Fig. 7). The monthly anomalies of deep water nitrate have shown relatively high interannual variation throughout the time-series, with strong negative values observed in 2010. This decline in deep water inventories may have an impact on overall phytoplankton production in the next production cycle, which may constrain growth of phytoplankton and the duration of blooms.

PHYTOPLANKTON BIOMASS

Vertical profiles of chlorophyll *a* at S27 continue to vary in terms of the magnitude and duration of the spring bloom (Fig. 8). The time-series of vertical chlorophyll *a* concentrations indicate relatively weak spring and autumn blooms in 2010 compared to average conditions. The record high levels of phytoplankton biomass associated with spring blooms during the early time-series were not apparent in 2010 despite the highly depleted levels of nitrate we noted at S27 (Fig. 6). This suggests that we may have missed the early part of the production cycle based on limited sampling in the early spring. Integrated chlorophyll *a* levels were below normal conditions but were only the 5th lowest in the time-series (Fig. 9). We use the criteria of integrated chlorophyll *a* levels >80 mg m^{-2} in upper 100 m to define start and end times of the spring phytoplankton bloom. The duration of the bloom in 2010 based on sampling observations was only 14 days, the 2nd lowest observed in the time-series compared to normal conditions of about 4 weeks (Fig. 10). The initiation of the bloom in 2010 was detected *in-situ* by early April with integrated concentrations in excess of 300 mg m^{-2} and was confirmed with MODIS Satellite Colour Imagery (Fig. 11). Peak concentrations of ~600 mg m^{-2} were detected in mid-April, after which levels declined rapidly below the threshold value consistent with satellite imagery. MODIS satellite imagery indicated that the spring bloom was initiated substantially earlier than normal in early March on the southern Grand Banks and reached peak levels by early April. Limited surface blooms were detected over the Grand Banks and northeast Newfoundland Shelf by late April with the exception of the Flemish Cap area. The inventories of chlorophyll *a* outside of the main spring bloom period have varied from ca. 30 to 60 mg m^{-2} over the past ten years with no apparent trend since the start of the sampling program (Fig. 10).

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 and in specific sub-regions of interest to enhance temporal and spatial coverage not possible based upon conventional sampling with vessels. Using a two-week MODIS 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 and autumn blooms which can vary from year to year across the Grand Banks and northeast Newfoundland Shelf.

The early development of patchy surface blooms was observed on the south-eastern areas of the Grand Banks by early March 2010 (Fig. 11). The spring bloom intensified rapidly to cover the whole of the Grand Banks in late March with concentrations of chlorophyll *a* >10 mg m^{-3}. The spring bloom progressed northward in early April to cover much of the northeast Newfoundland Shelf while surface concentrations were greatly reduced on the Grand Banks (Fig. 11). By the time of our spring oceanographic survey, in mid-April 2010, chlorophyll *a* concentrations were reduced to near-background levels over much of the northwest Atlantic with the exception of the Gulf of St. Lawrence and Gulf of Maine. Similarly, the patchy distribution of near-surface chlorophyll *a* concentrations across the sections and higher surface concentrations restricted to the northern sections (Bonavista, White Bay and Seal Island) during the summer 2010 survey was also supported by MODIS composite imagery. The summer 2010 colour imagery also indicated extensive surface phytoplankton blooms across the central Labrador Sea and Hudson Strait, consistent with observations in previous years. Extensive cloud cover during the autumn survey limited our capacity to detect the areal extent of surface blooms (particularly above the northeast Newfoundland Shelf), which appear to be at background levels near 1 mg m^{-3} over much of the Grand Banks with slightly elevated levels observed on the southeast shoal and Slope waters (Fig. 11).

At larger scales, the statistical sub-regions off Newfoundland and Labrador indicate that the magnitude of surface phytoplankton blooms detected by MODIS was generally higher in 2010 compared to previous years, particularly in the southern and central sub-regions (Fig. 12). In general, the surface blooms occurred earlier, were more intense and in some cases longer in duration compared to previous years. Limited blooms were detected on the northern Labrador Shelf in 2010 and were weaker compared to normal conditions. The timing and magnitude of the spring bloom on the southern Labrador Shelf was earlier and followed the pattern on the northeast Shelf and northern Grand Banks. The occurrence of autumn blooms, which is sometimes not captured well by conventional sampling, is supported by the high-resolution MODIS imagery across all statistical sub-regions. The satellite data indicate slightly higher surface chlorophyll *a* concentrations across all sub-regions in autumn 2010 compared to average conditions.

OCEAN ACIDIFICATION

Mean pH varied from 8.1 to 8.3 throughout the upper 200 m across the summer 2010 sections (Fig. 13). In general, pH levels were higher near surface and tended to decrease with depth and changes coincided with differences in temperature and presumably water mass structure across the Newfoundland and Labrador Shelves. The highest pH measurements were observed along the northern Labrador Section (Beachy Island) and the northeast Newfoundland Shelf (White Bay and Bonavista) while the lowest values were observed at depths in excess of 100 m along the outer Shelf across the Flemish Cap section (Fig. 13). Ocean pH measurements during the autumn survey were nearly identical to summer values but over a narrower range (Fig. 14). We detected pH minima again at depths in excess of 100 m along the outer Shelf of the Flemish Cap and southeast Grand Bank sections.

FIXED STATION – ZOOPLANKTON

There was strong seasonality in the abundance of many zooplankton species included in the analysis of Station 27. Most species show a single peak in abundance during late spring or early summer (e.g., *Calanus glacialis*, *Calanus hyperboreus*), although in some instances the peak is relatively protracted in duration (e.g., *Calanus finmarchicus* and *Pseudocalanus* spp.). Larvaceans appear to show two small peaks in abundance, one following the spring phytoplankton bloom, and another in the fall. Still others peak in late fall and early winter (e.g., *Oithona* spp., *Metridia* spp.). The pattern of seasonality for pelagic gastropods and euphausids generally shows a gradual increase, often peaking in mid to late summer. Note that although some species occur regularly at Station 27, their abundance or frequency of occurrence is too low to obtain accurate estimates of seasonal variability.

A generalized linear model which included the effects of year and month as categorical variables was used to estimate interannual variations in the overall abundance of the 16 dominant zooplankton taxa present at Station 27. After careful study, the analytical procedure applied in 2008 and onward was different from that used in previous years by using individual abundance estimates as independent observations instead of monthly averages. The result is that the overall estimated mean is lower than during the period prior to 2008, as a result of estimating the average from data that follow a skewed distribution, but interannual patterns of variations are highly correlated with prior estimates.

Data for 2010 were incomplete at the time of this report. This may have resulted in some bias in the estimates of abundance for 2010 but the analytical model applied to the data should have compensated to some degree for the missing information. Analytical results indicated that all species demonstrate a statistically significant seasonal cycle in 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). In addition, all sixteen species showed significant interannual variations in overall abundance (Fig. 15). In 2008, the abundance of all three species of *Calanus* spp. was very low, as was the abundance of many other taxa. Since then, the abundance of most large copepods has increased to above average levels, with only *Calanus glacialis* and large copepod nauplii being at roughly average levels. The abundance of the small copepods *Microcalanus* sp., *Oithona* sp., *Pseudocalanus* sp. and *Oncaea* sp. reached peak or near-peak levels while that of the warm water species *Acartia* sp., *Centropages* sp., and *Temora longicornis* were at low levels of abundance. The abundance of euphausids decreased in abundance since 2008 while *Sagitta* sp. increased. Pelagic gastropods were at their highest level since the start of the programme while larvaceans have shown little change over most of the time-series, with the exception of very low levels of abundance in 1999 and 2006 that were ~10-fold lower than the norm.

In 2008, the biomass of copepods at S27 reached its lowest level since the inception of our monitoring activities but levels rebounded significantly in 2009 and 2010 when biomass reached a level comparable to the highest value on record in 2002 (Fig. 16). The increase was largely the result of significant increases in the abundance of *Calanus finmarchicus* and *Calanus hyperboreus*, as well as the continued increasing trend in the abundance of *Metridia* sp., as well as the high abundance of small copepods (Fig. 17). Biomass peaked in late autumn, which is consistent with the most frequently observed seasonal pattern, but biomass in late 2009 reached the highest levels observed since the onset of collections at S27.

The seasonal succession of copepodites stages of *Calanus finmarchicus* and *Pseudocalanus* sp. has followed a similar pattern each year throughout the time-series of observations at S27 (Fig. 18). The peak in relative abundance of young CI-CIII copepodites of *Calanus finmarchicus* occurs around June/July, with a secondary peak sometime in late autumn in some years. Pre-adult CV and adult CVI stages dominate throughout most of the year, but in 2009, a greater abundance of CIV copepodites late in the year and into the early part of 2010 may indicate that the second cohort may have been of greater importance than in most previous years. Similar circumstances occurred in the case of *Pseudocalanus* sp. but with a prolonged presence of CIII and CIV stages relative to previous years. For both species, the greater abundance of intermediate copepodite stages resulted in a heightened abundance of these two species during late summer and autumn. The persistence of increased densities of *Calanus finmarchicus* and *Pseudocalanus* sp. is not entirely unusual but the greater than normal abundance may be indicative of enhanced productivity.

OCEANOGRAPHIC SECTIONS – ZOOPLANKTON

As in previous years, we estimated the abundance of 27 taxa of zooplankton collected on the southeast Grand Banks, Flemish Cap, Bonavista Bay and Seal Island oceanographic sections (Figs. 19-22). Because of the broad diversity of taxa, the number of sections and the increasing length of the time-series of observations, we will not discuss the recent patterns of variations of individual species but instead focus on the overall patterns of variation of functional groups (small copepods, meroplankton, large copepods and carnivorous zooplankton) (Figs. 23-24). The information was combined to reflect the definition of ecoregions of Pepin et al. (2010) on the Newfoundland Shelf: data from the Bonavista Bay and Seal Island section are combined for the northern ecoregion (Newfoundland Shelf) and data from the southeast Grand Banks and Flemish Cap sections are combined to represent the southern ecoregion (Grand Banks). To combine the information among years and section, each time-series (species and section) was standardized to a mean of 0 for the period of 1999–2010, and a standard deviation of 1 to yield yearly anomalies. The time-series for each functional group and sections within each ecoregion were then combined to produce box whisker plots showing the 5th, 25th, 50th, 75th and 95th percentiles of the information, along with outliers.

In the northern ecoregion, all four functional groups demonstrated similar long term patterns of variation, with the lowest abundances being recorded at the start of the time-series (1999), with a gradual increase to a peak or plateau between 2004 and 2006 (Fig. 23). Since then, the abundance of small and large copepods has hovered close to the long term mean, with greater variability among taxa being observed in small copepods relative to larger species. Meroplanktonic taxa, after increasing from 1999 to 2000, have shown no significant trend over time, with interannual variations in median abundance generally less than 1 standard deviation from the mean. The abundance of carnivorous zooplankton reached their highest levels in 2004 after which the median abundance among taxa has been slightly below the long term mean, except in 2006 when it was slightly above.

The abundance of zooplankton in the southern ecoregion is somewhat distinct from that on the northern portion of the region. Abundance was lowest in 1999 but the increase that followed reach a peak or plateau in 2001 or 2002, earlier than in the north (Fig. 24). Since then, there has been no clear trend in any of the functional groups. There are indications that 2009 and 2010 are characterized by generally higher levels of abundance than in previous years, with more than 60 % of taxa from each functional group having abundance levels above their long term mean, with meroplankton and large copepods exhibiting the greatest overall increase.

The patterns of variation in the composite information presented in Figs. 23 and 24 are not generally the result of random patterns of variation in individual taxa from year-to-year but instead reflect the overall long term patterns of variation exhibited by most taxa in each of the ecoregions (Figs. 19–22). The patterns of variation of individual taxa often exhibit considerable serial correlation in the abundance of animals over the period of 4+ years. These variations in abundance are only weakly associated with the fluctuations in the composite physical index for the entire Newfoundland Shelf and Grand Banks.

REGIONAL SUMMARY OF THE STATE OF THE OCEAN

Scorecard indices were developed as a method of summarizing the many variables used to represent the state of lower trophic levels. To simplify the information, the time-series of the annual estimate of inventory or abundance for each summary variable was standardized to a mean of zero (for the period 1999–2010) and unit standard deviation ([observation–mean]/SD). The standard deviation provides a measure of the variability of an index. The result of this standardization yields a series of anomalies. The scorecard serves to illustrate departures from the long term mean across the range of variables by colour coding anomalies as either being above (red) or below (blue) the long term average, with darkening shades serving to represent the increasing magnitude of that departure. This is similar to the approach adopted for summarizing AZMP's physical variables (AZMP Bulletin, 2008). For the chemical-biological observations, the key variables selected were: (1) near surface (0-50 m) and deep (50-150 m) nitrate inventories, and (2) chlorophyll inventories (0-100 m), the magnitude, timing, and duration of the spring bloom, and zooplankton abundances (*C. finmarchicus, Pseudocalanus spp*., total copepods, and total non-copepods) for the fixed station and seasonal section surveys.

The scorecard for the NL region could not be completed in its entirety because of delays in processing nutrient samples collected in 2010. Nevertheless, annual nitrate inventories (shallow and deep) have been at low levels since 2008 and appear be continuing to decrease in 2010 based on the observations at S27 and the Seal Island section (Fig. 25). Deep inventories of nitrate in November-December, a precursor index of the potential for production in the coming year, reached the lowest levels on record in 2009, and conditions at S27 appear to have remained low by the end of 2010.

Chlorophyll concentrations in 2009 were at their highest levels since the start of AZMP activities in the region but returned to near normal values in 2010 (Fig. 25). The lowest levels were recorded in 2003. The spring phytoplankton bloom at S27 has been later than normal since 2008 but the timing of that event in 2010 was close to normal, albeit a little late. The magnitude of the bloom has been lower than normal since 2008 but as with the timing the trend going into 2009-10 has been toward a return to average conditions. Delayed onset of the bloom at S27 is also associated with a decrease in the duration of peak phytoplankton biomass near the coast. In fact, there is a very strong ($r = -0.92$, $P < 0.01$) negative relationship between the timing of the spring phytoplankton bloom and its duration. The magnitude of the bloom is also weakly positively correlated with its duration ($r = 0.43$, $P > 0.05$), although that association is not statistically significant.

In 2009 and 2010, the principal zooplankton indices indicated that abundance was generally higher than average, with densities reaching their highest levels in 2010 along many of the oceanographic sections (Fig. 25). There was evidence of a north-to-south gradient in the anomalies in zooplankton abundance in 2009 and 2010, with conditions nearer to the long term average in the north and higher than average in the region of the Grand Banks (S27, Flemish and southeast GB sections) but this trend was not consistent for all zooplankton indices in all years. The abundance anomaly of *Pseudocalanus* sp. was high in both ecoregions in 2010 but the greatest increased occurred in the north relative to other parts of the region.

The indices of inventories and abundances across trophic levels (nutrients, phytoplankton and zooplankton) generally exhibit weak associations (i.e., correlations) between adjacent trophic levels. Average annual chlorophyll abundance anomalies, an index of phytoplankton biomass, are weakly correlated with the anomalies in surface nitrate inventories ($r = -0.28$, $P > 0.05$) (Fig. 25) suggesting that conditions that allow phytoplankton to grow in abundance result in greater depletion of surface nutrients. There is also a weak positive association between the anomalies in phytoplankton abundance and those of *Calanus finmarchicus*, copepods and non-copepod zooplankton across the region ($r = 0.25$, 0.27 and 0.20, respectively. All values $P > 0.05$) but again the association is very weak, suggesting the concept of trophic cascades may be difficult to apply based on annual indices of abundance. There are stronger correlations among the zooplankton indices, with anomalies in the abundance of *Calanus finmarchicus* showing strong correlations with those of total copepod abundance ($r = 0.70$, $P > 0.05$) as well as those of non-copepod zooplankton ($r = 0.67$, $P > 0.05$), but a weaker correlations with the patterns of abundance of *Pseudocalanus* sp. ($r = 0.29$, $P > 0.05$). Although the latter is also positively correlated with the variations in the abundance of total copepods ($r = 0.40$, $P > 0.05$) and non-copepods ($r = 0.26$, $P > 0.05$), the relationships are weaker than that of the index of large copepod abundance.

ENVIRONMENTAL FORCING AND BIOGEOCHEMICAL STATE

Throughout much of the 12 years covered by AZMP activities, the physical environment of the NL region has been in a period characterized by warm saline water relative to the long term (1981–2010) average (Fig. 25), although salinities have been variable and closer to the long term mean, as has the North Atlantic Oscillation index (winter atmospheric pressure difference between Greenland and the Azores). The standardized anomalies of the physical descriptors of the environment from 1999 to 2010 had ranges of 1.5 to 4.1, with an average range of 2.4 and a standard deviation of 0.74. These statistics imply that variability in the physical environment was generally less than has been observed over the last 30 years, and that very high values were achieved in recent times, mostly in terms of high temperatures and low indices of ice extent and duration or in the amount of cold intermediate water in the region. Therefore, the range of conditions observed in the last 12 years did not reflect the cold and fresh extremes observed in the mid-80's and early-90's. When contrasted with decades going back to 1950, the decade of AZMP observations has demonstrated the lowest intra-decadal variability, reflecting the warming trend throughout much of the region.

During the period 1999-2010, the indices of zooplankton abundance had an average variability of ~0.8 (min=0.1; max=2.1), meaning that on average the abundance of zooplankton taxa along oceanographic section varied by a factor of ~20–30 over the twelve years of observations, with roughly 13 % of estimates showing variations of two orders of magnitude or more (i.e., 100-fold +). Variations in nutrient levels were not as extreme but they have demonstrated significant interannual changes in abundance, as have indices of phytoplankton abundance across the region.

In an attempt to conduct an exploratory analysis aimed at investigating whether there are indications that changes in the physical environment have resulted in changes in the inventories of nutrients or in the abundance of phytoplankton or zooplankton, we evaluated the correlation between all environmental variables and all estimates of nutrient, phytoplankton and zooplankton taxa from all sections and S27. Based on a 12 year time-series, significant correlations would occur at $-0.576 \leq r \geq 0.576$.

There was no single environmental variable that demonstrated a widely consistent pattern of correlations with either nutrient inventories, phytoplankton abundance or with the wide diversity of zooplankton taxa (Figs. 27–29). There was some indication that phytoplankton abundance at S27 demonstrated consistent significant negative correlations with indices of atmospheric conditions from Cartwright to Nuuk and the NAO (Fig. 27). Surface nutrients were negatively correlated with environmental indices in 85 of 130 cases, deep nutrient inventories were negatively correlated with 51 of 130 cases, and phytoplankton abundance was negatively correlated in 85 of 130 cases. Also, 59 % of the 3080 correlations of environmental variables with indices of zooplankton abundance from the oceanographic sections were positive and 4.6 % of the correlations were significantly positive while only 1.4 % were significantly negative (Fig. 28). All these departures are highly significantly different than would be expected by chance. The abundance indices of dominant species *Oithona similis* and *Calanus finmarchicus*, as well as a few other species, did appear to have a greater proportion of positive correlations with environmental variables than the data of all taxa combined (Fig. 29), but the environmental variables that were significantly correlated at $P > 0.05$ differed for the indices of abundance from different oceanographic sections. This might suggest that different processes are affecting the patterns of abundance across different portions of the region. For example, the abundance indices of these two species from the Flemish Cap and southeast Grand Banks sections tend to be significantly positively correlated with atmospheric variables whereas on the Seal Island section strong positive correlations tend to be associated with indices of water column temperature.

The results of such a generalized exploratory analysis suggest that no single environmental index provides strong predictive capacity in the patterns of variation in chemical and biological state of the environment on the Newfoundland Shelf and Grand Banks. A more comprehensive and hypothesis driven analysis will be required to evaluate the bottom-up mechanisms that influence production of lower trophic levels in the region. It is also possible that the environmental conditions in the region have not varied sufficiently during the 12 years of AZMP activities to allow an accurate assessment of the response of ecosystem productivity to changes in physical drivers of the system.

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 above their long term (1999–2010) 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. 2011), 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. 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 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 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.

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. Only with continued and possibly expanded monitoring activities coupled with focussed modelling programs which can be challenged with our observation base will such an objective be achieved.

SUMMARY

- The onset of deepening of the mixed-layer that normally begins in the early autumn was delayed considerably by ca. 1 month at S27, in contrast to average conditions.
- The seasonal development of stratification at the fixed station was also delayed compared to earlier years.
- The inventory of nitrate within the upper 50 m and deep layers at S27 was the lowest observed since the start of the time-series in 1999.
- MODIS satellite imagery indicated that the surface blooms occurred earlier, were more intense and in some cases longer in duration in 2010 in contrast to previous years.
- The abundance of most large copepods at S27 in 2009 and 2010 has increased significantly since the low levels observed in 2008. Only *Calanus glacialis* and large copepod nauplii remain at near average levels.
- The abundance of the small copepods *Microcalanus* sp., *Oithona* sp., *Pseudocalanus* sp. and *Oncaea* sp. reached peak or near-peak levels while that of the warm water species *Acartia* sp., *Centropages* sp., and *Temora longicornis* were at low levels of abundance.
- On the Bonavista and Seal Island sections, all four functional groups of zooplankton (small and large copepods, meroplankton and carnivores) demonstrated similar long term patterns of variation, with the lowest abundances being recorded at the start of the time-series (1999), with a gradual increase to a peak or plateau between 2004 and 2006, after which small and large copepods as well as carnivores have returned to values that are near the long term average.
- The abundance of zooplankton on the Flemish Cap and southeast Grand Banks sections in 2009 and 2010 are characterized by generally higher levels of abundance than in previous years, with more than 60 % of taxa from each functional group having abundance levels above their long term mean.
- Across the region, annual nitrate inventories (shallow and deep) have declined since 2008 and appear be continuing to decrease in 2010.
- Average pH in surface (<50 m) and deeper (>50 m) waters were approximately 8.23 and 8.15 during the summer and autumn surveys. In general, ocean pH levels on the

Newfoundland and Labrador Shelves were slightly elevated when compared to average levels noted in the Arctic and in the Labrador Sea.

- Chlorophyll concentrations in 2009 were at their highest levels since the start of AZMP activities in the region but returned to near normal values in 2010.
- In 2009 and 2010, the principal zooplankton indices indicated that abundance was generally higher than average, with densities reaching their highest levels in 2010 along many of the oceanographic sections.
- The indices of inventories and abundances across trophic levels (nutrients, phytoplankton and zooplankton) generally exhibit weak associations (i.e., correlations) between adjacent trophic levels
- There was no single environmental variable that demonstrated a widely consistent pattern of correlation with either nutrient inventories, phytoplankton abundance or with the wide diversity of zooplankton taxa. This may be the result that over the last decade the physical environment of the Newfoundland shelf showed the lowest overall variability relative to previous decades going back to 1950.

ACKNOWLEDGMENTS

We thank Catherine Andrews, Wade Bailey, Eugene Colbourne, Joe Craig, Charlie Fitzpatrick, Paula Hawkins, Jennifer Hidgon, 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.

REFERENCES

Caldeira, K., and Wickett, M.E. 2003. Anthropogenic carbon and ocean pH. Nature, **425**: 365.

Fabry, V.J., Seibel, B.A., Feely, R.A., and Orr, J.C. 2008. Impacts of ocean acidification on marine fauna and ecosystem processes. ICES J. Mar. Sci. **65**: 414–432.

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. Hydrog. Ocean Sci. 223, 23 pp.

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. Hydrog. 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 Res. **35**: 855-879.

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, 24 p.

Pepin, P., Colbourne, E.B., and Maillet, G.L. 2011. Seasonal patterns in zooplankton community structure on the Newfoundland Shelf and western Labrador Sea. Prog. Oceanogr. doi:10.1016/j.pocean.2011.01.003.

Ries, J.B., Cohen, A.L,. and McCorkle, D.C. 2009. Marine calcifiers exhibit mixed responses to CO_2-induced ocean acidification. Geology, **37**: 1131-1134.

Richardson, A.J., Walne, A.W., John, A.W.G., Jonas, T.D., Lindley, J.A., Sims, D.W., Stevens, D., and Witt, M. 2006. Using continuous plankton recorder data. Prog. Oceanogr. **68**: 27-74.

Warner, A.J., and Hays, G.C. 1994. Sampling by the continuous plankton recorder survey. Prog. Oceanogr. 34: 237-256.

Table 1. Listing of AZMP Sampling Missions in the Newfoundland and Labrador Region in 2010. The transects are Southeast and Southwest St. Pierre Bank (SESPB/SWSPB); Southeast Grand Banks (SEGB); Flemish Cap (FC); Bonavista Bay (BB); Funk Island (FI); Smith Sound (SS); White Bay (WB); Seal Island (SI); Avalon Channel (S27); Makkovik Bank (MB); Beachy Island (BI), 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, zooplankton, and including partial occupations) profiles provided for each seasonal section and fixed station occupations.

Mission ID	Dates	Sections/Fixed	# Hydro Stns	# Bio Stns
TEL971	Apr 15-May 4, 2010	SESPB/SWSPB, SEGB, FC, BB, FI, SS, S27	129	81
TEL973	July 8-24, 2010	FC, BB, WB, SI, MB, BI	106	62
Hud983	Nov 23-Dec 11, 2010	SEGB, FC, BB, TB	108	48
Fixed	Jan-Dec 2010	S27	41	19

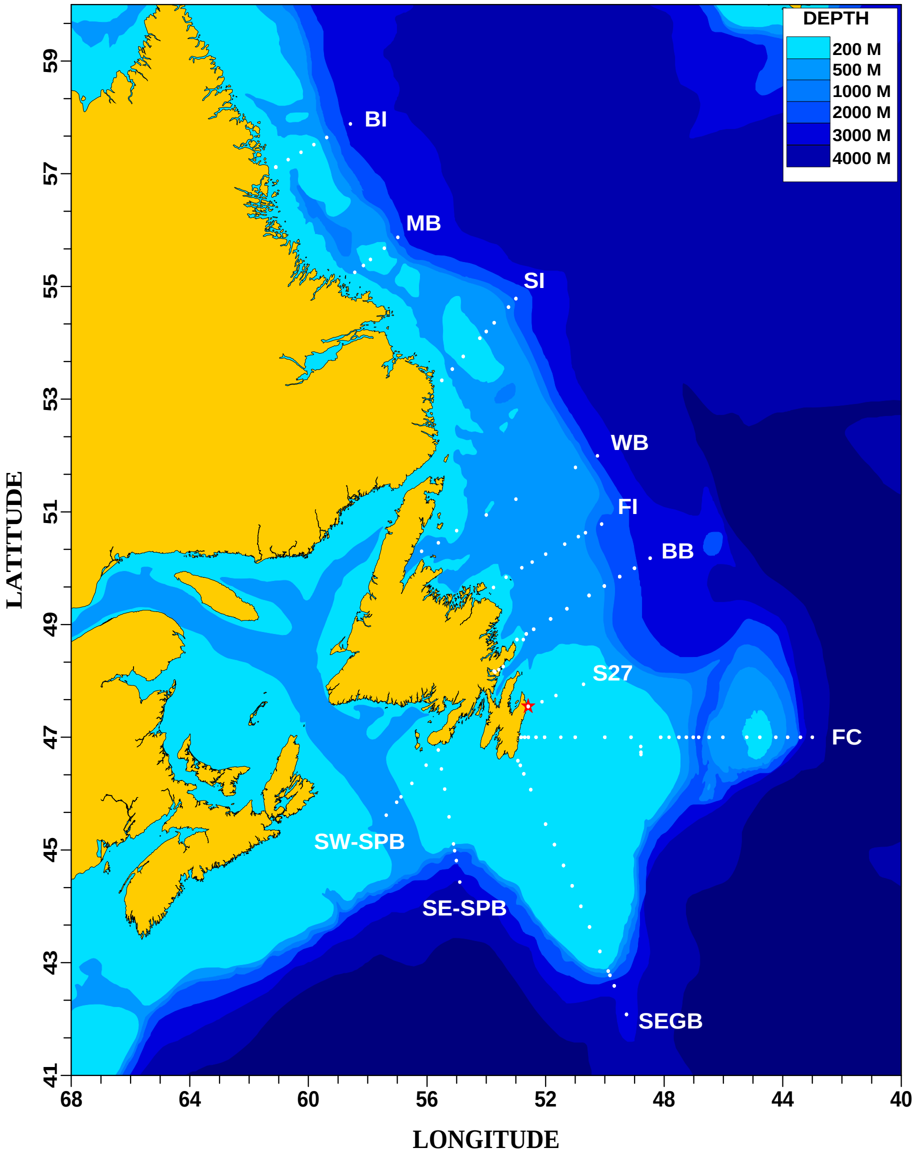


Figure 1. Primary sections and biological stations occupied in the Newfoundland and Labrador region during 2010. The AZMP primary sections include Seal Island (SI), Bonavista Bay (BB), Flemish Cap (FC), and Southeast Grand Banks (SEGB). The sections sampled north of SI are only sampled during summer (MB=Makkovik Bank; BI=Beachy Island). The southern Grand Bank sections (SW-SPB and SE-SPB=southwest and southeast St. Pierre Bank, and SEGB = Southeast Grand Banks) are typically only sampled during spring and autumn. Additional sections occupied in 2010 include White Bay (WB; summer), Funk Island (FI; spring), and S27 (S27; spring).

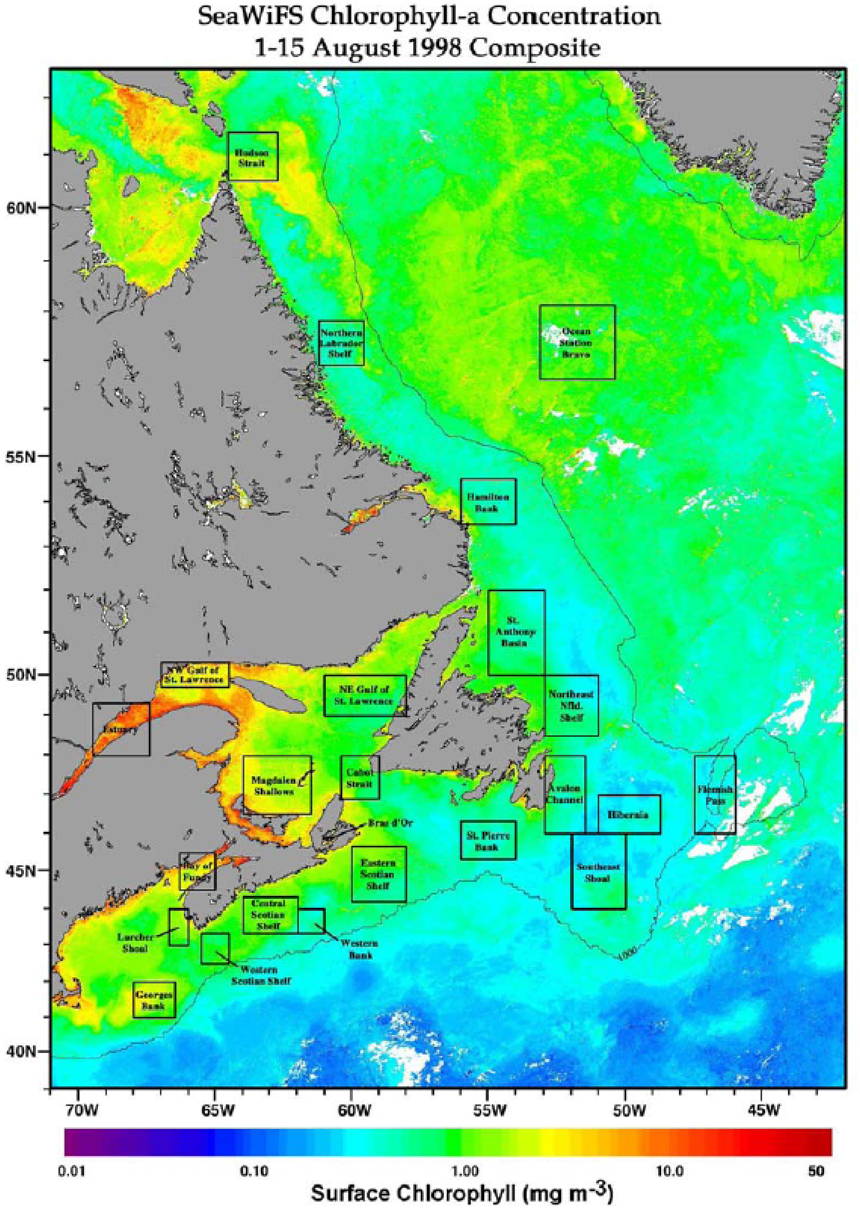

SeaWiFS Chlorophyll-a Concentration
1-15 August 1998 Composite

Figure 2. Statistical sub-regions in the Northwest Atlantic identified for spatial/temporal analysis of SeaWiFS/MODIS ocean colour data.

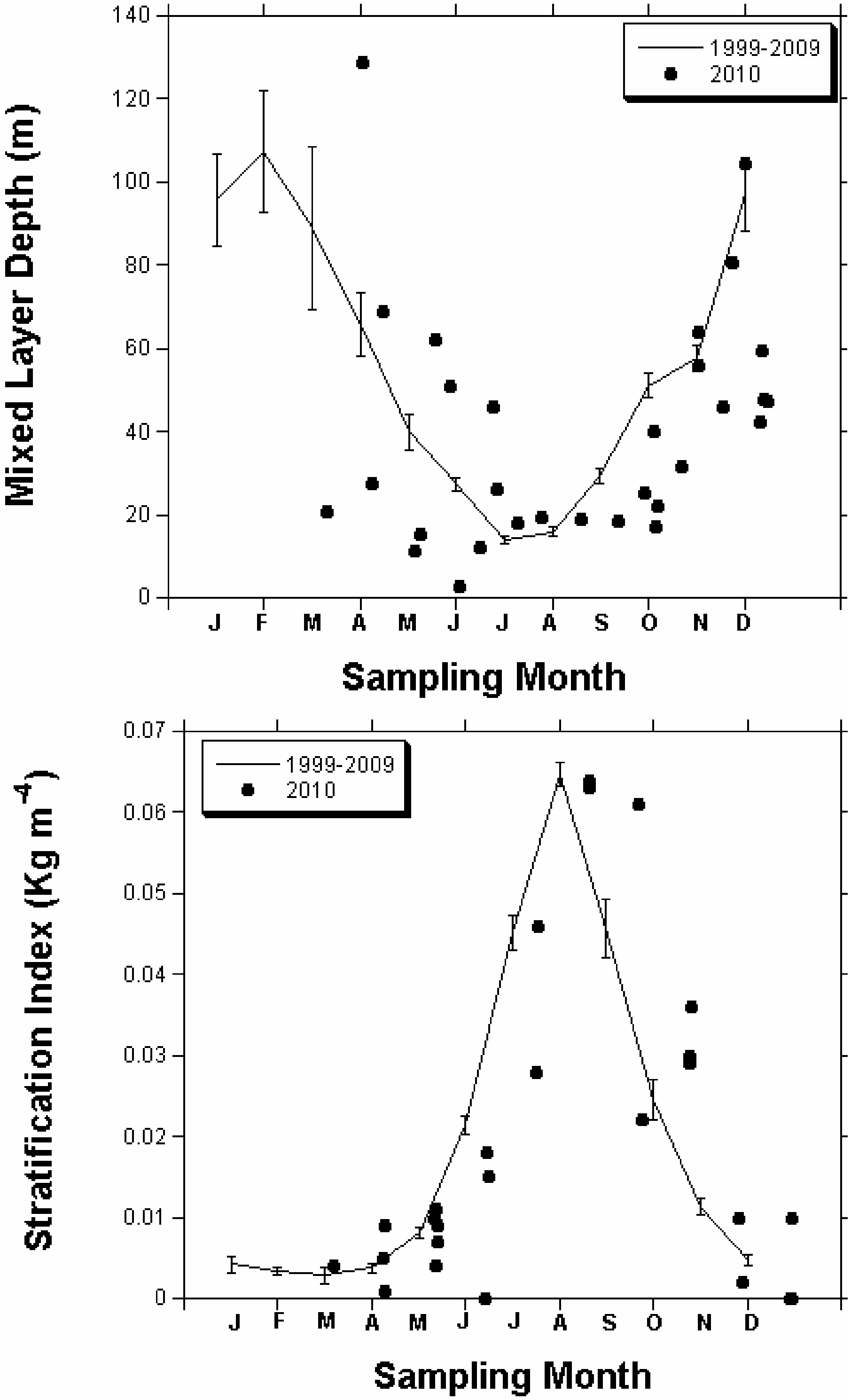


Figure 3. Mixing properties (mixed-layer depth, stratification index) at S27. Year 2010 data (circles) compared with mean conditions from 1999-2009 (solid line). Vertical lines are standard errors of annual means.

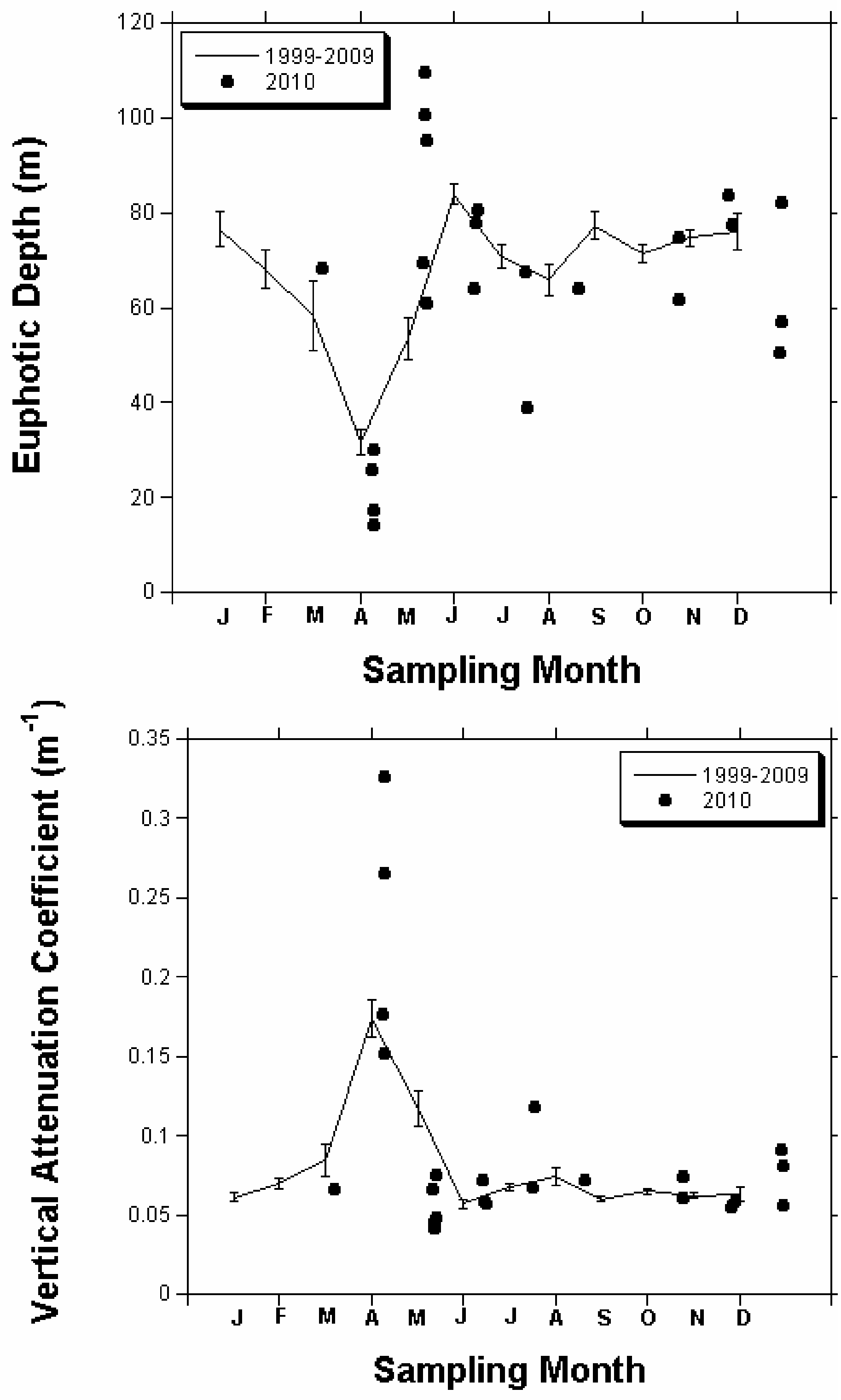


Figure 4. Optical properties (euphotic depth and vertical attenuation from PAR irradiance meter) at S27. Year 2010 data (circles) compared with mean conditions from 1999 to 2009 (solid line). Vertical lines are standard errors of annual means.

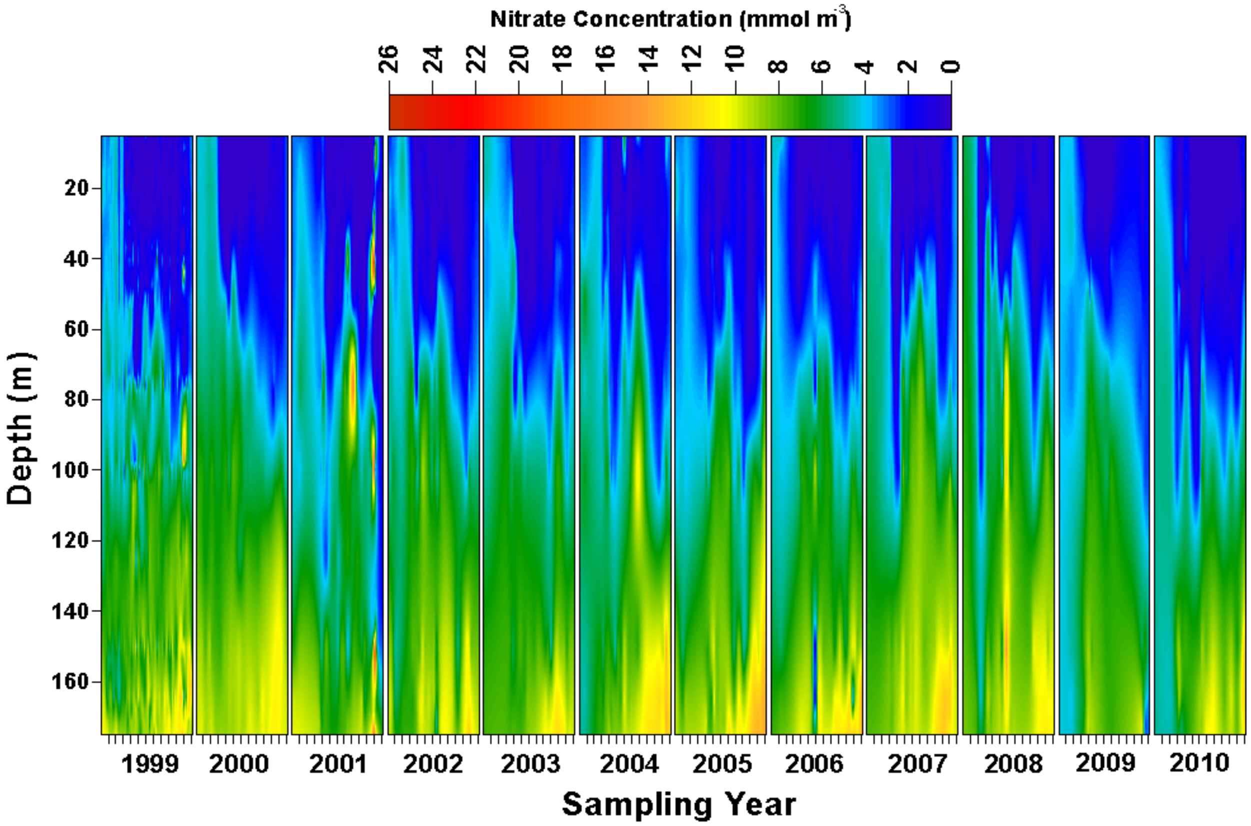


Figure 5. Time-series of vertical nitrate structure at S27.

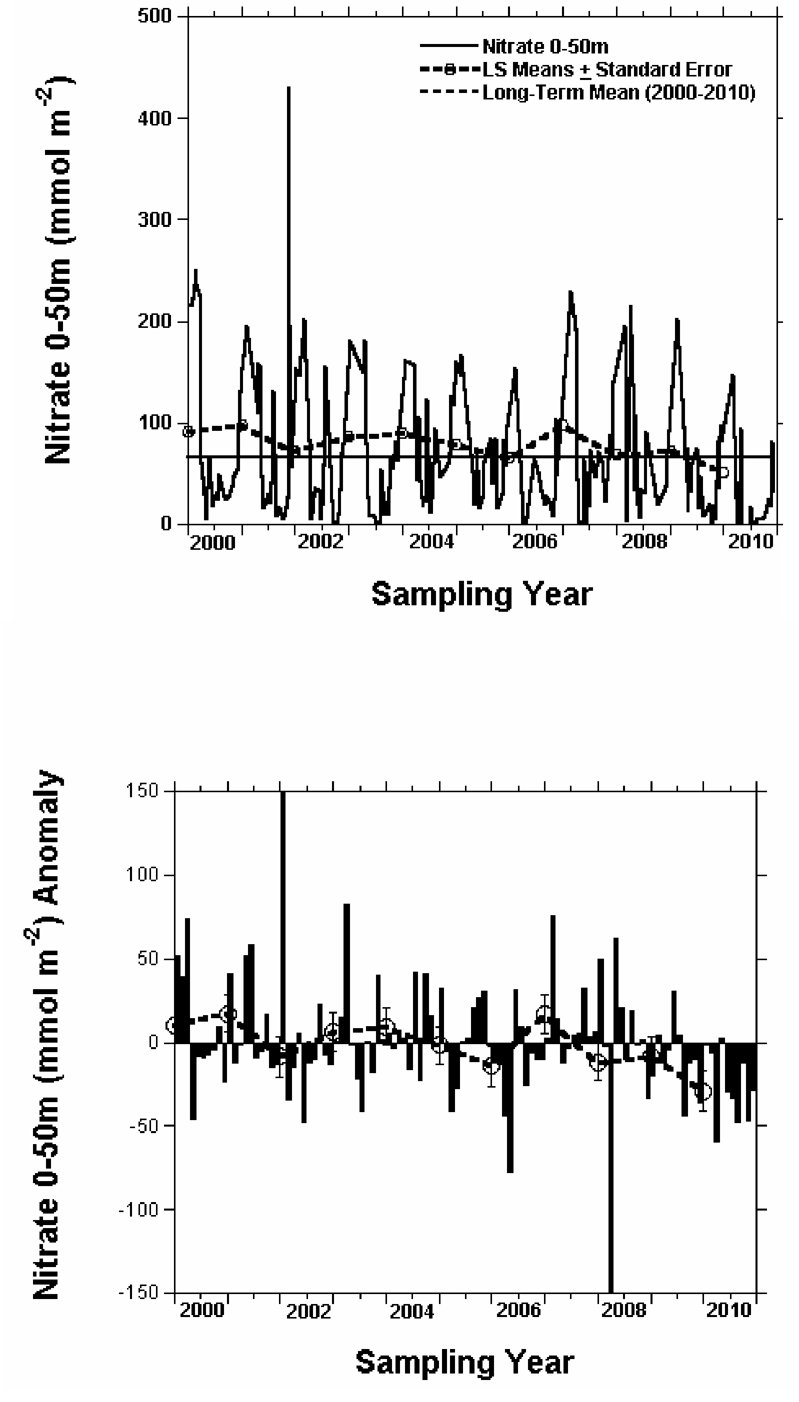


Figure 6. Time-series of 0-50 m nitrate inventories at S27 (solid line); annual least squares means (dashed line) with standard errors from linear regression model and long-term average (solid line), top panel. Bottom panel: Monthly anomaly time-series of 0-50 m nitrate inventories at S27 (vertical bars), and least squares annual means (dashed line) ± standard errors (vertical bars).

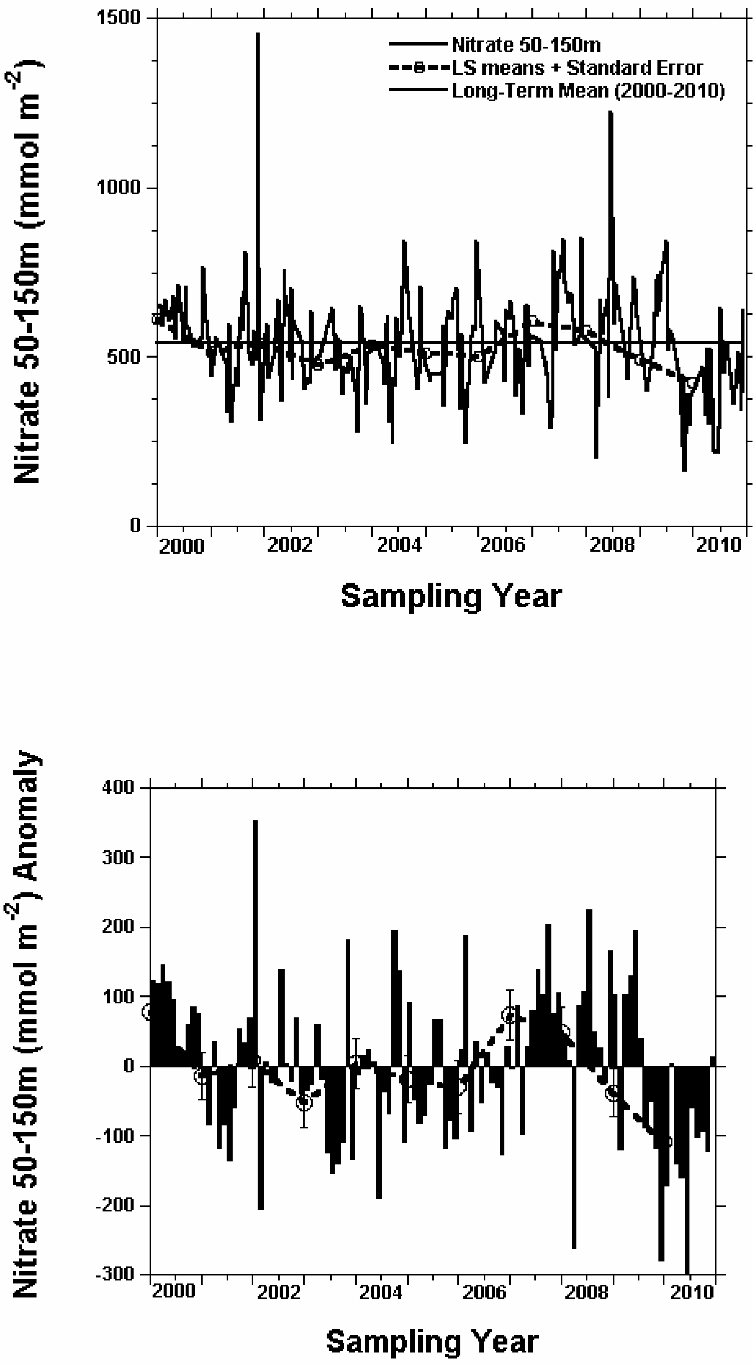


Figure 7. Time-series of deep (50-150 m) nitrate inventories at S27 (solid line); annual least squares means (dashed line) with standard errors from linear regression model and long-term average (solid line), top panel. Bottom panel: Monthly anomaly time-series of 50-150 m nitrate inventories at S27 (vertical bars), and least squares annual means (dashed line) ± standard errors (vertical bars).

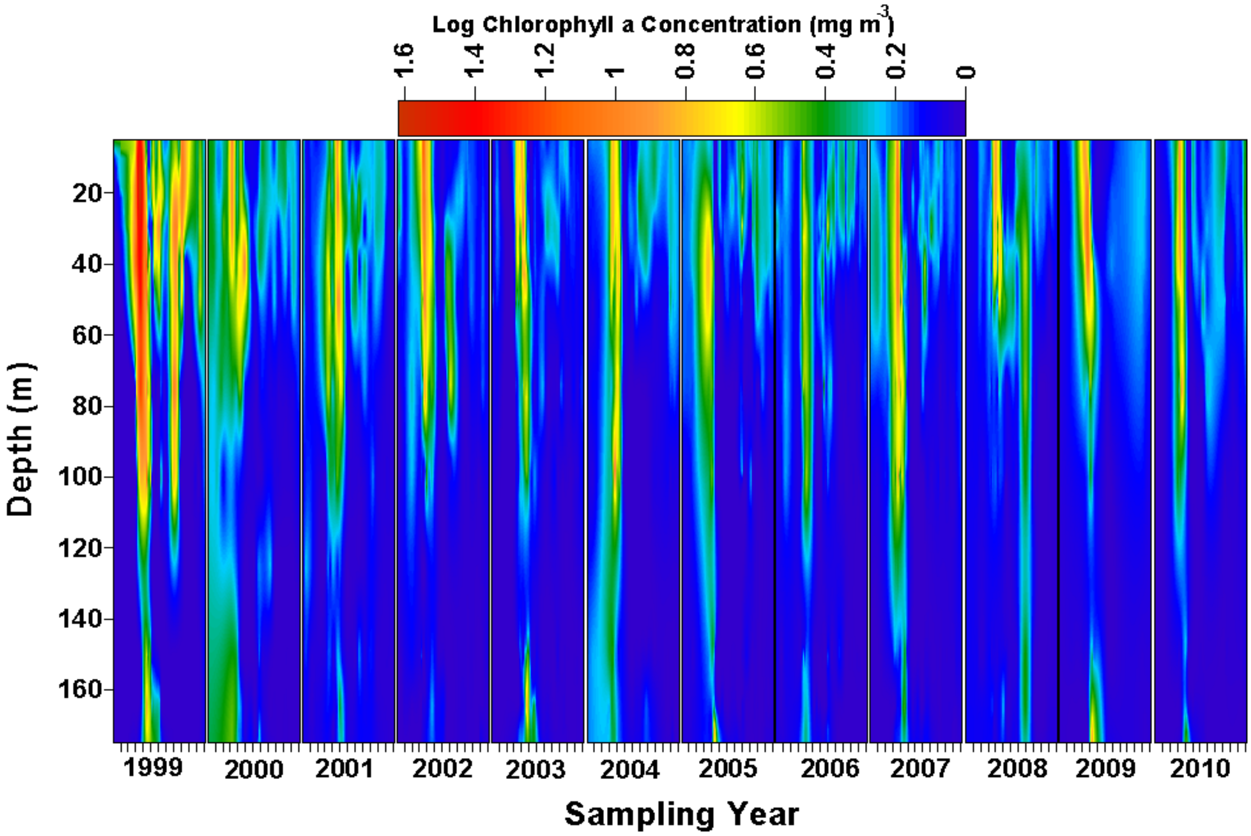


Figure 8. Time-series of vertical chlorophyll a structure at S27.

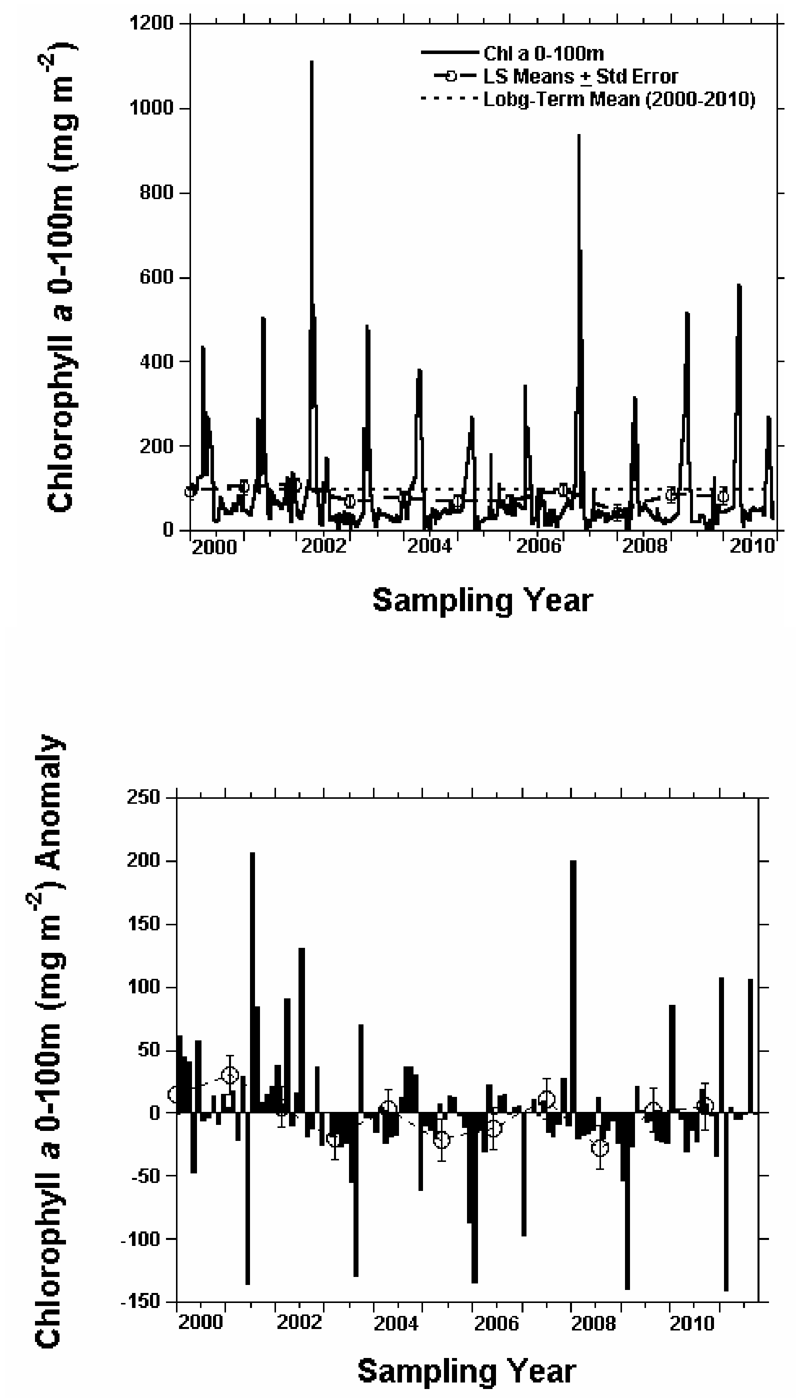


Figure 9. Time-series of chlorophyll a (0-100 m) inventories at S27 (solid line); annual least squares means (dashed line) with standard errors from linear regression model and long-term average (dashed line), top panel. Bottom panel: Monthly anomaly time-series of chlorophyll a inventories at S27 (vertical bars), and least squares annual means (dashed line) ± standard errors (vertical bars).

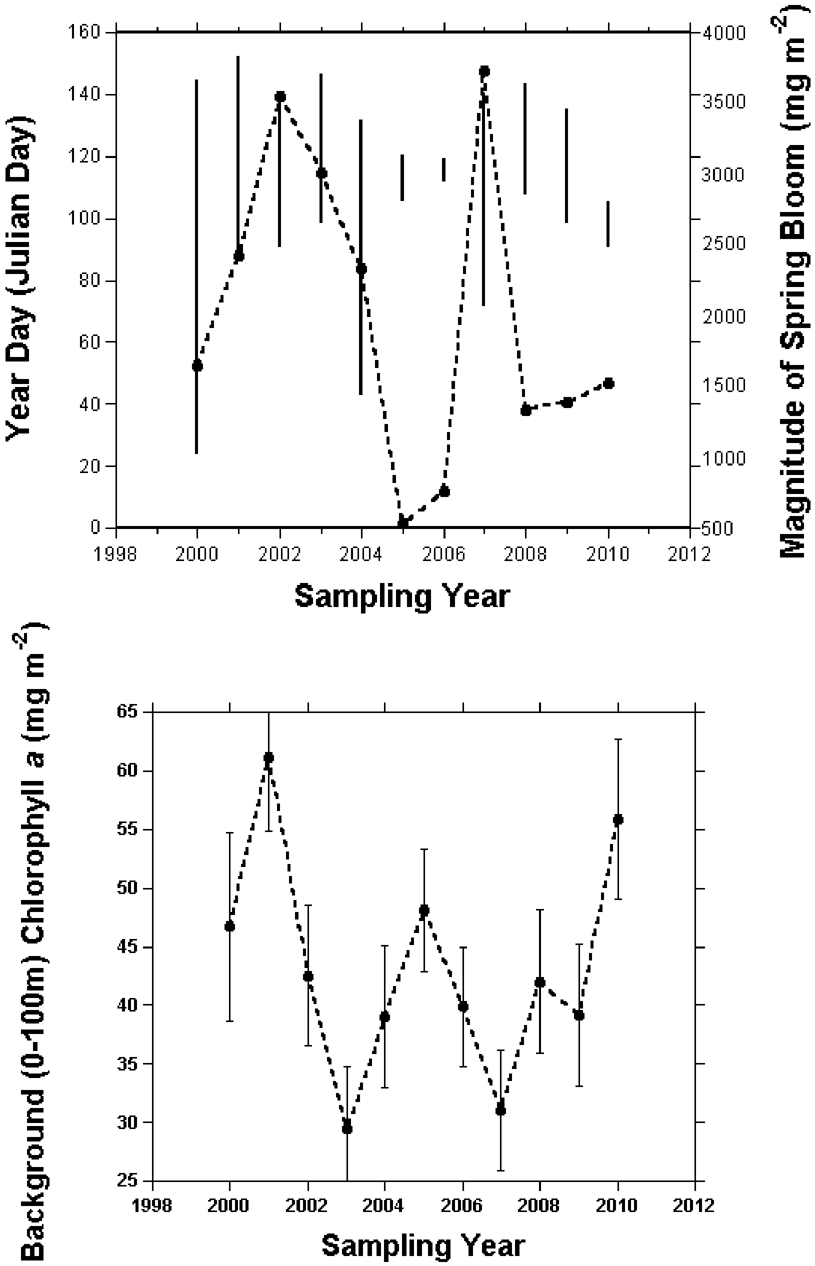


Figure 10. Dynamics of the spring phytoplankton bloom at S27, 2000-2010: Top panel showing timing, duration (based on 80 mg m^{-2} of chlorophyll a threshold for determining start and end of the bloom – vertical bars), and magnitude (dashed line); and bottom panel showing "background" chlorophyll a levels, i.e., outside of spring bloom periods (least squares annual averages ± SE; dashed line).

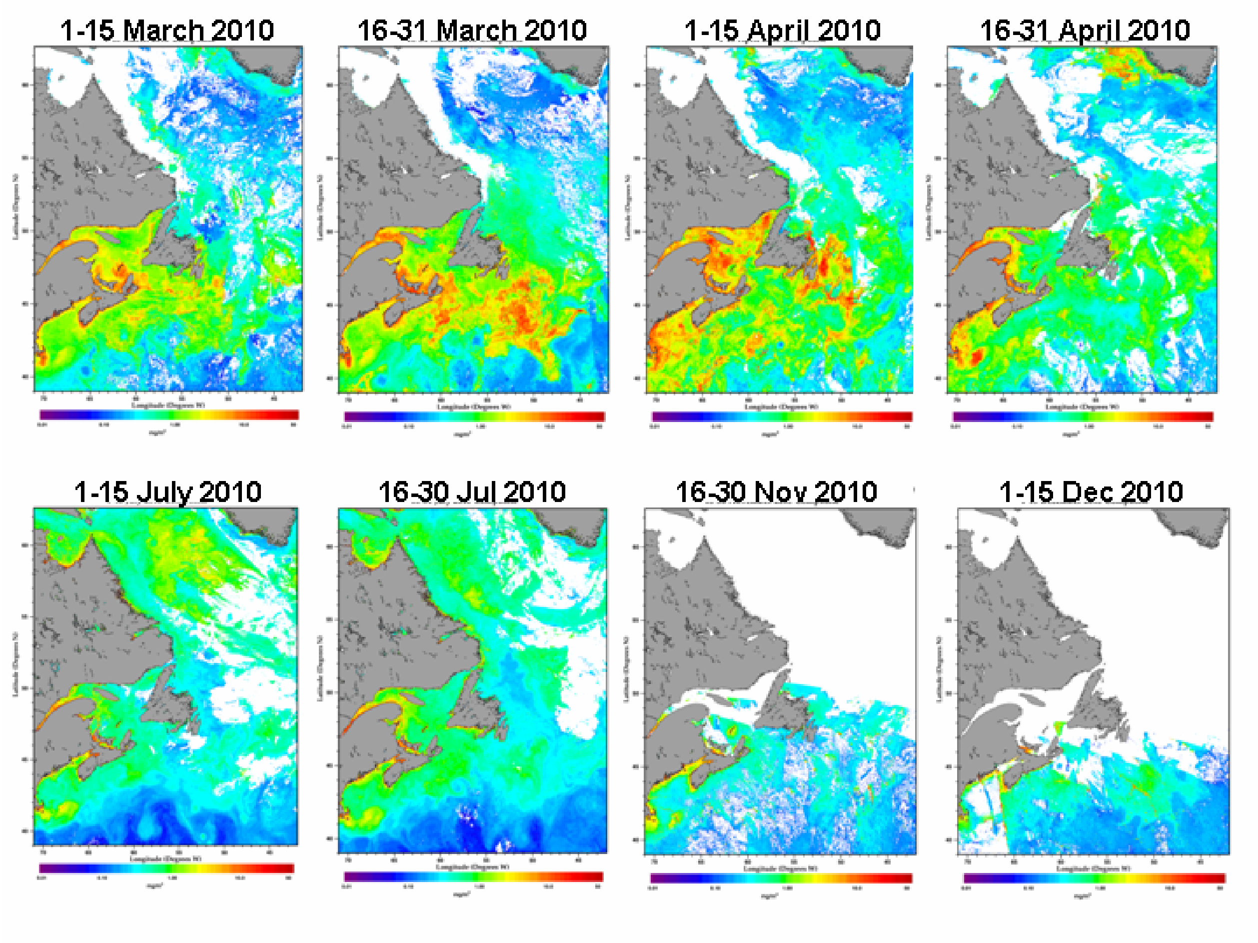


Figure 11. MODIS semi-monthly composite images of surface chlorophyll a concentrations in the NW Atlantic region before the start of the ocean monitoring program (March 2010 imagery) and during AZMP seasonal (April, July, November-December months) surveys in 2010 (see Table 1 for Mission dates). Data resolution is approximately 2 Km per pixel.

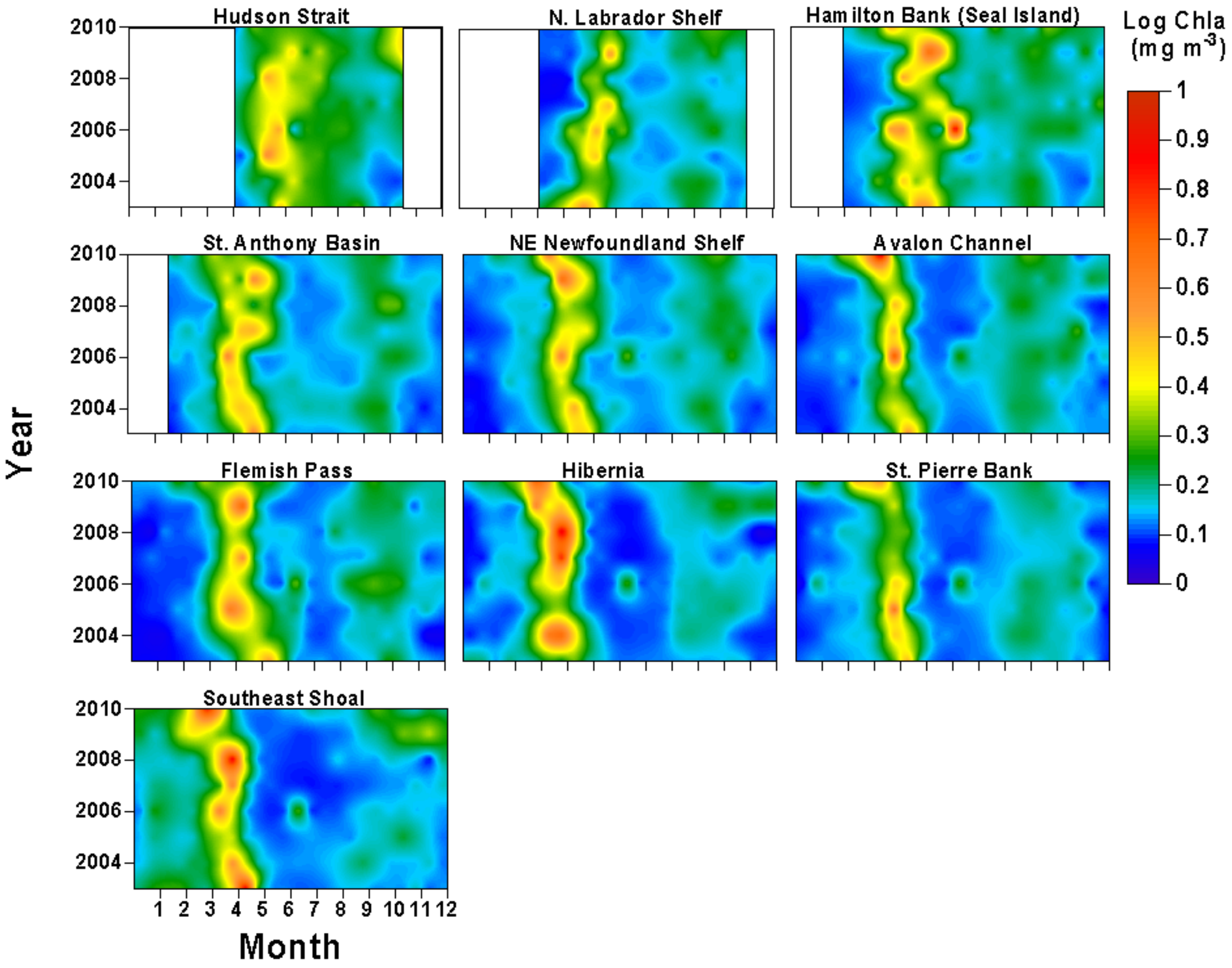


Figure 12. Time-series of surface chlorophyll a concentrations (mg m-3), from bi-weekly MODIS ocean colour data along statistical sub-regions across the Newfoundland and Labrador area. See Figure 2 for locations of statistical sub-regions.

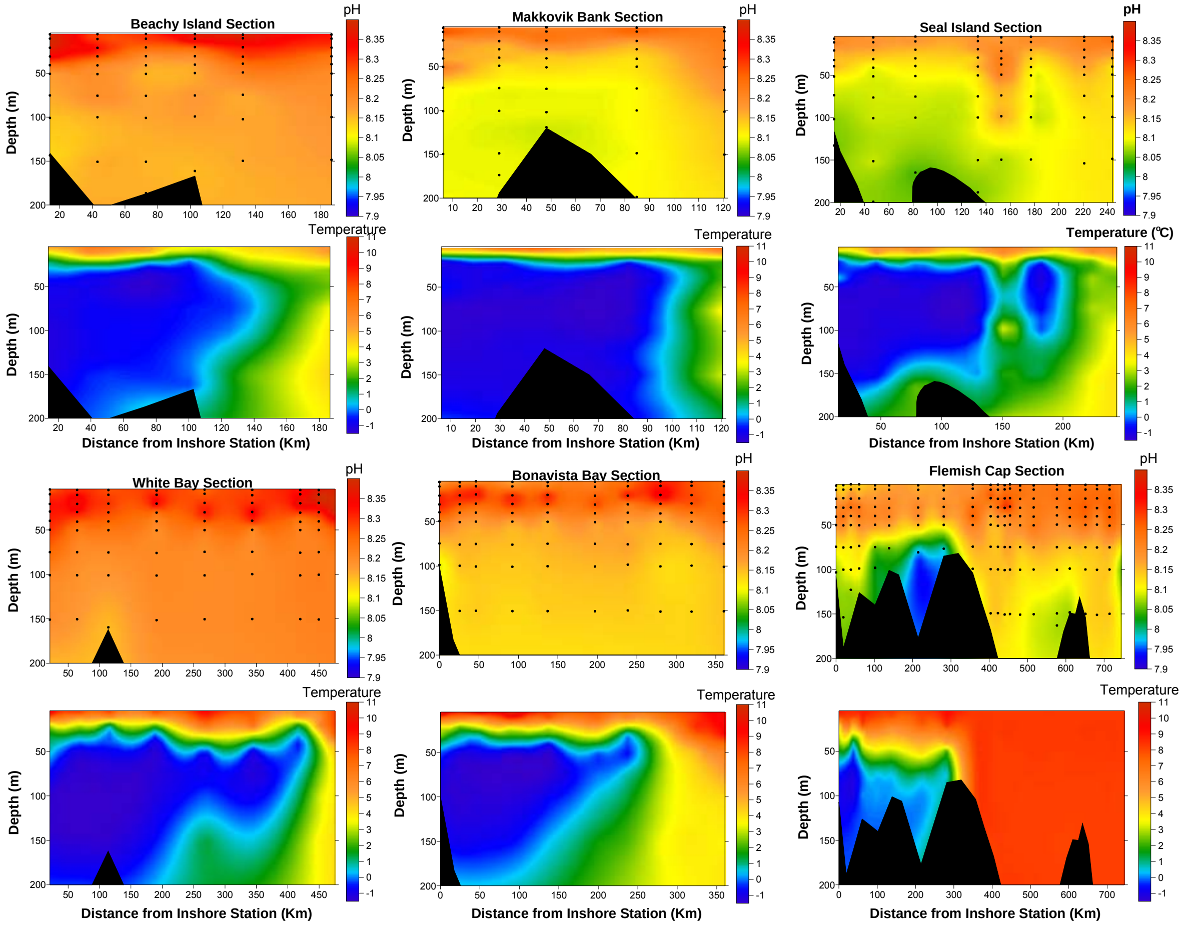


Figure 13. Vertical profiles of ocean pH and temperature across the summer 2010 seasonal oceanographic survey. All pH and temperature scales are identical for easier inter-comparisons. Mean statistics for pH are provided at the upper left hand-corner for each profile.

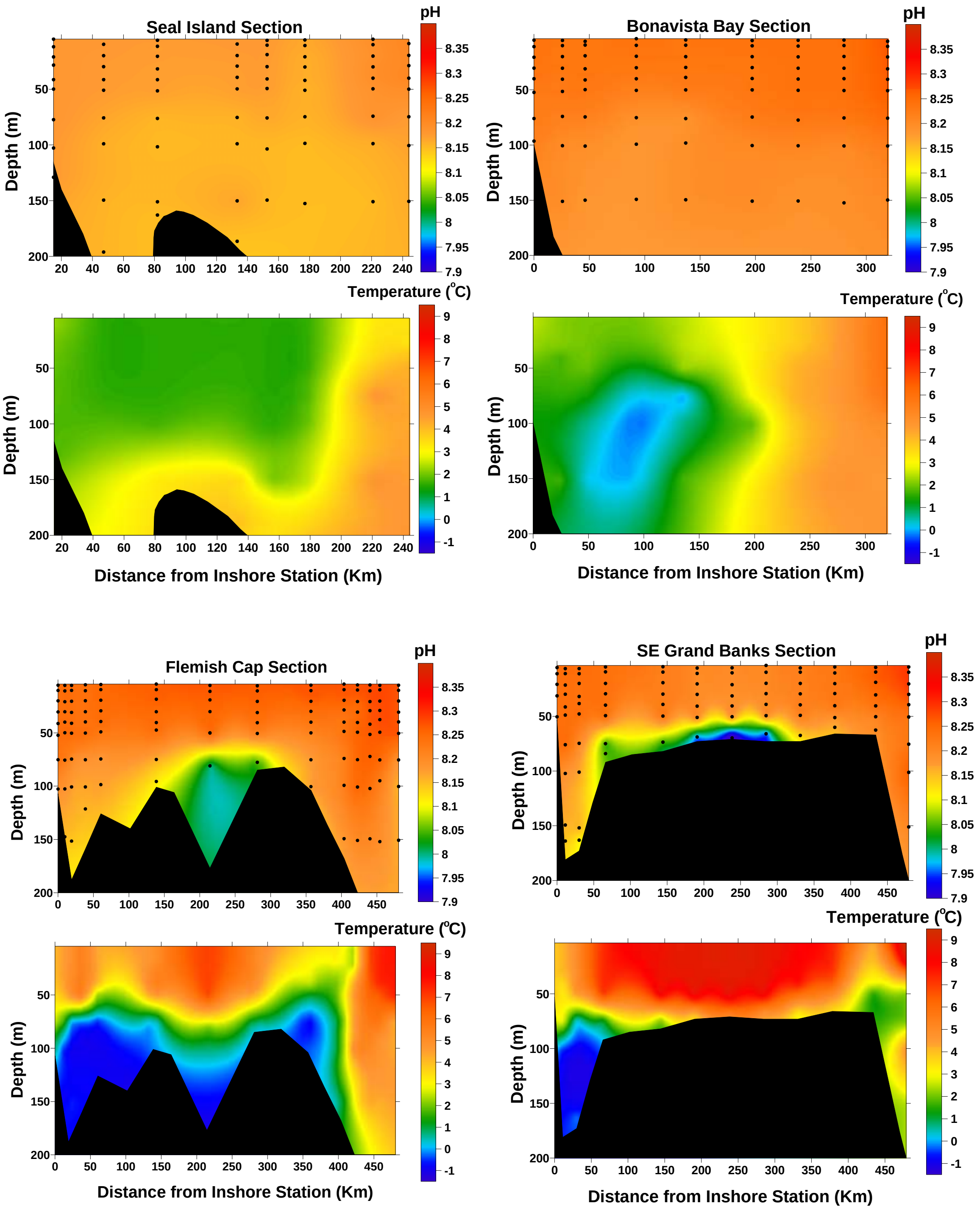


Figure 14. Vertical profiles of ocean pH and temperature across the autumn 2010 seasonal oceanographic survey. All pH and temperature scales are identical for easier inter-comparisons. Mean statistics for pH are provided at the upper left hand-corner for each profile.

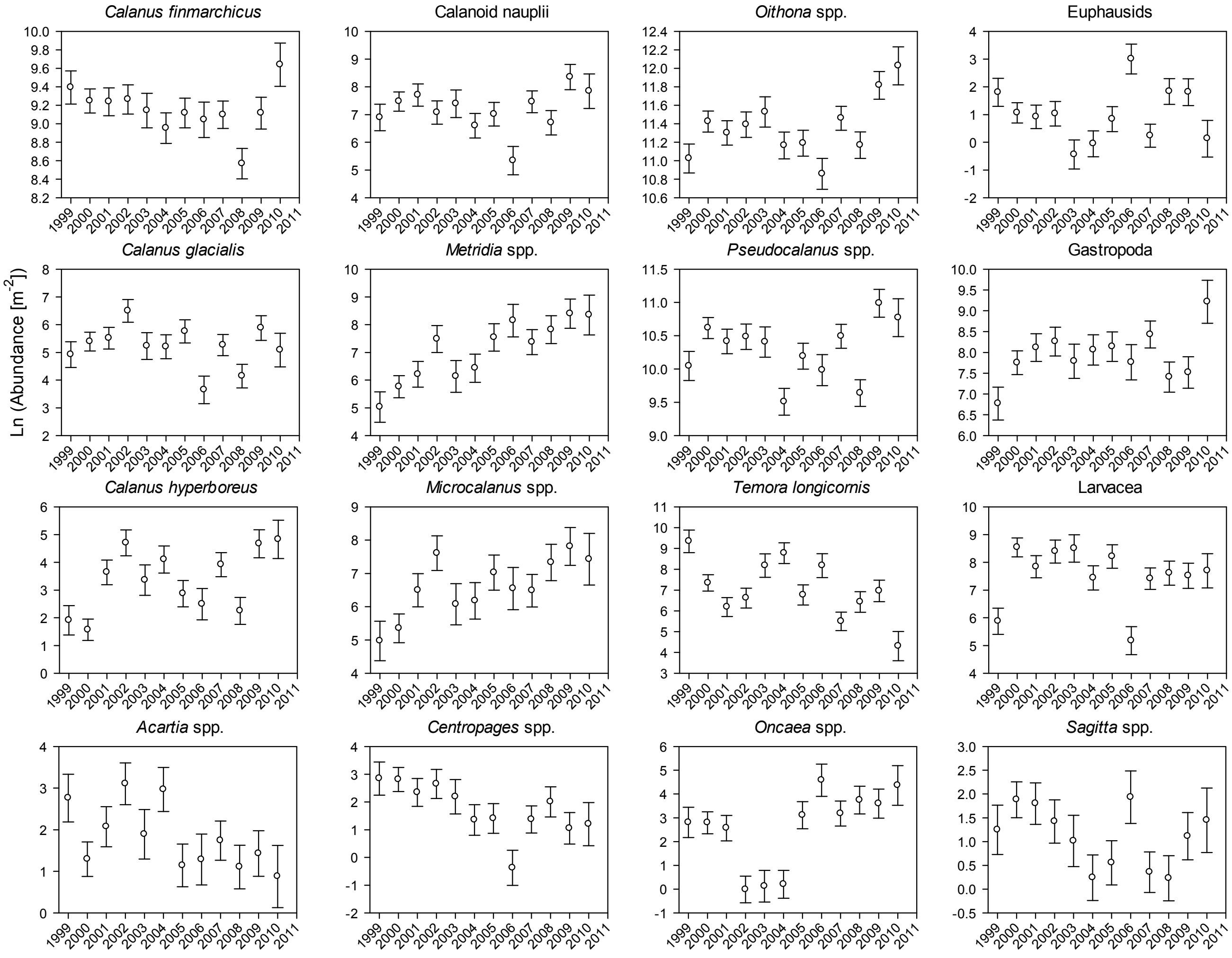


Figure 15. Seasonally-adjusted estimate of the mean abundance of twelve dominant zooplankton taxa from Station 27 for the period 1999-2010. The error bars represent standard errors.

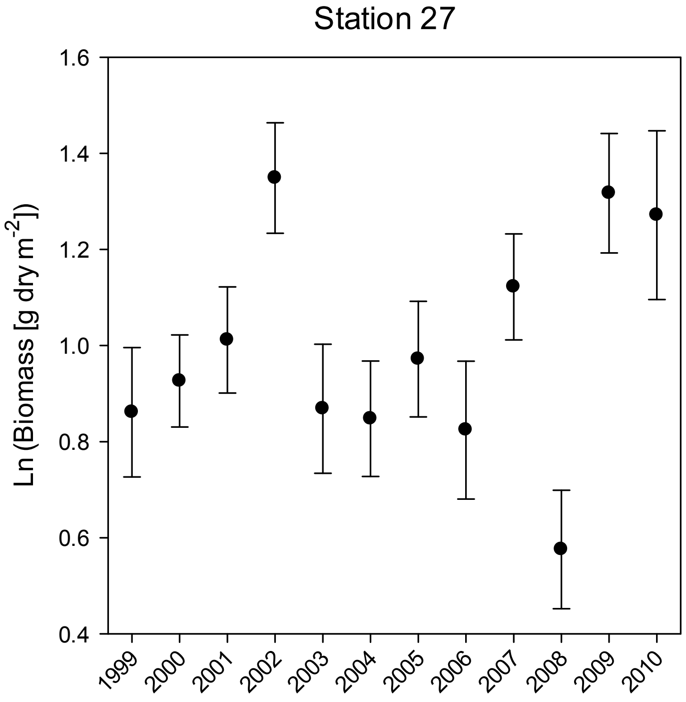


Figure 16. Seasonally-adjusted estimates of the mean biomass of 8 dominant copepod species from Station 27 for the period 1999-2010. The error bars represent standard errors.

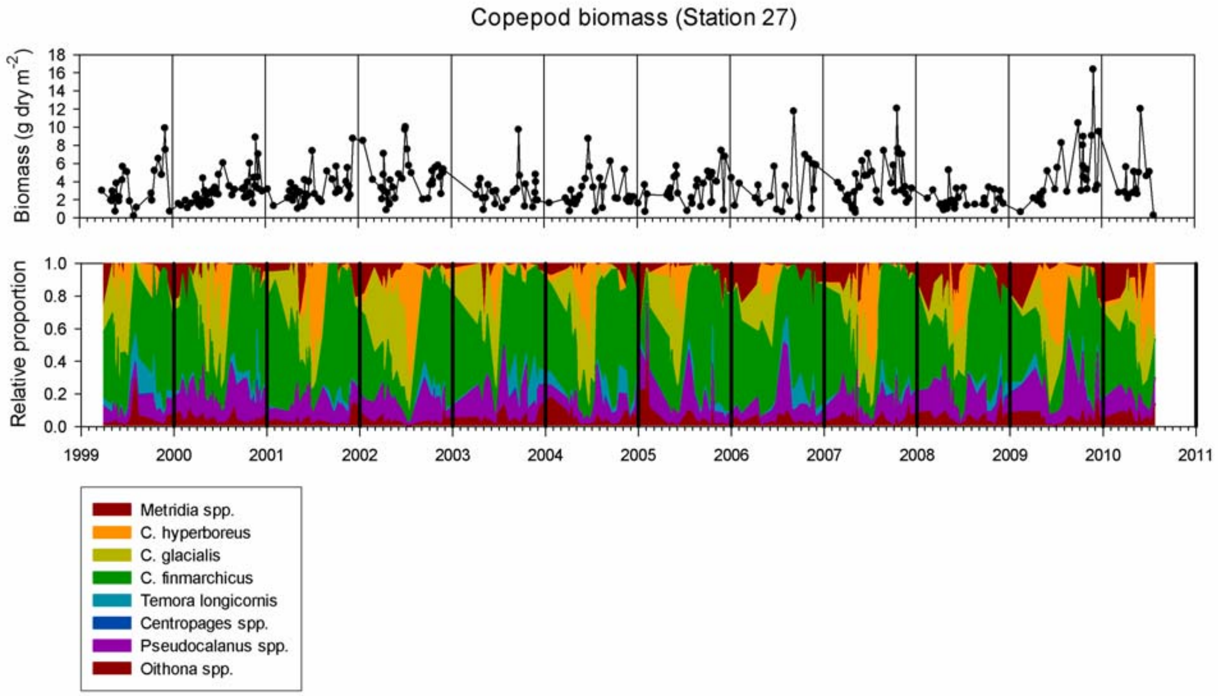


Figure 17. Seasonal cycle of total biomass and species distribution of the dominant copepods at Station 27 for the period 1999-2010. The vertical order of the species in the lower panel is the same as in the legend.

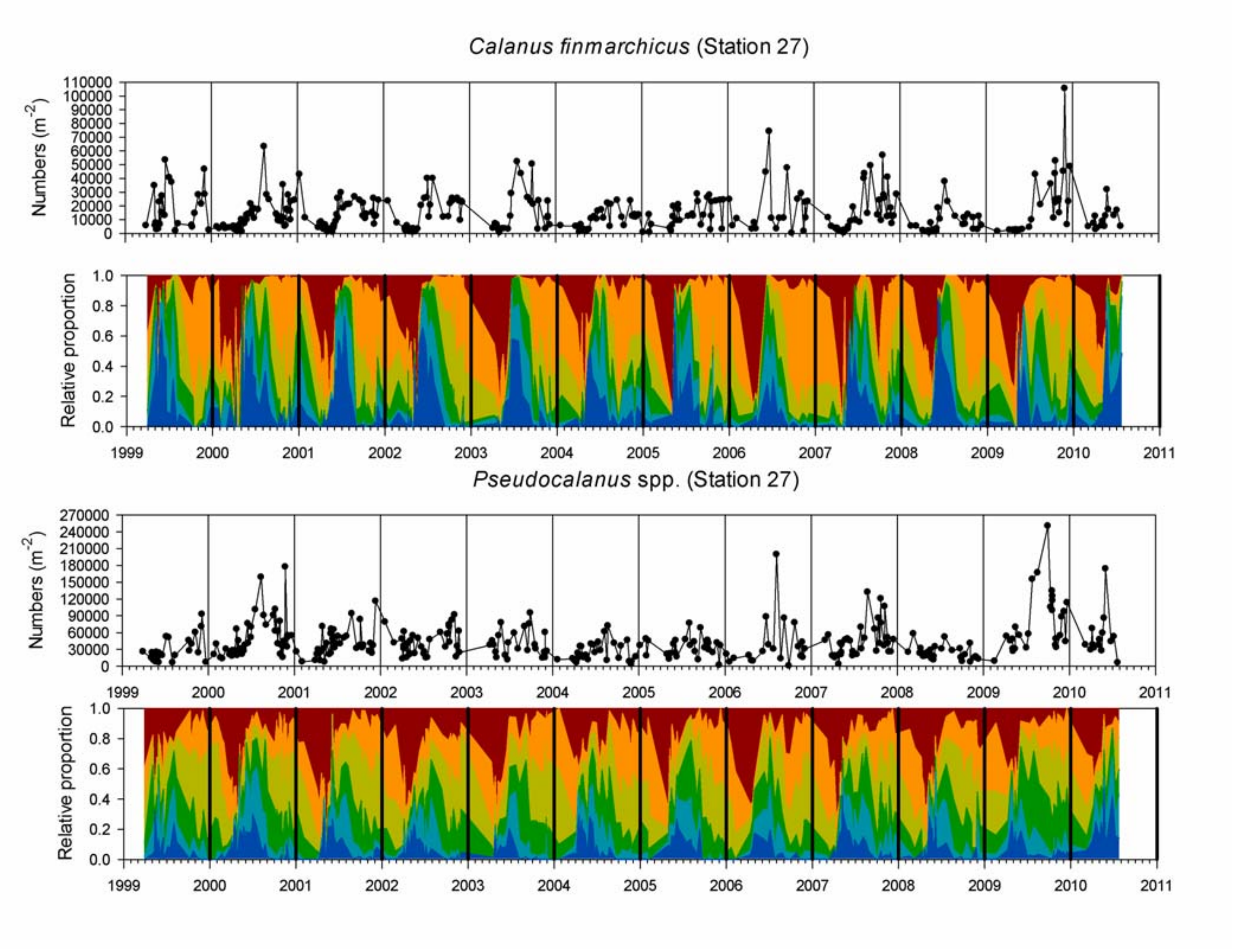


Figure 18. Seasonal cycle of abundance and stage distribution of Calanus finmarchicus and Pseudocalanus spp. at Station 27 for the period 1999-2010. (Stage CI (blue), CII (teal), CIII (green), CIV (yellow), CV (orange), CVI (brown)).

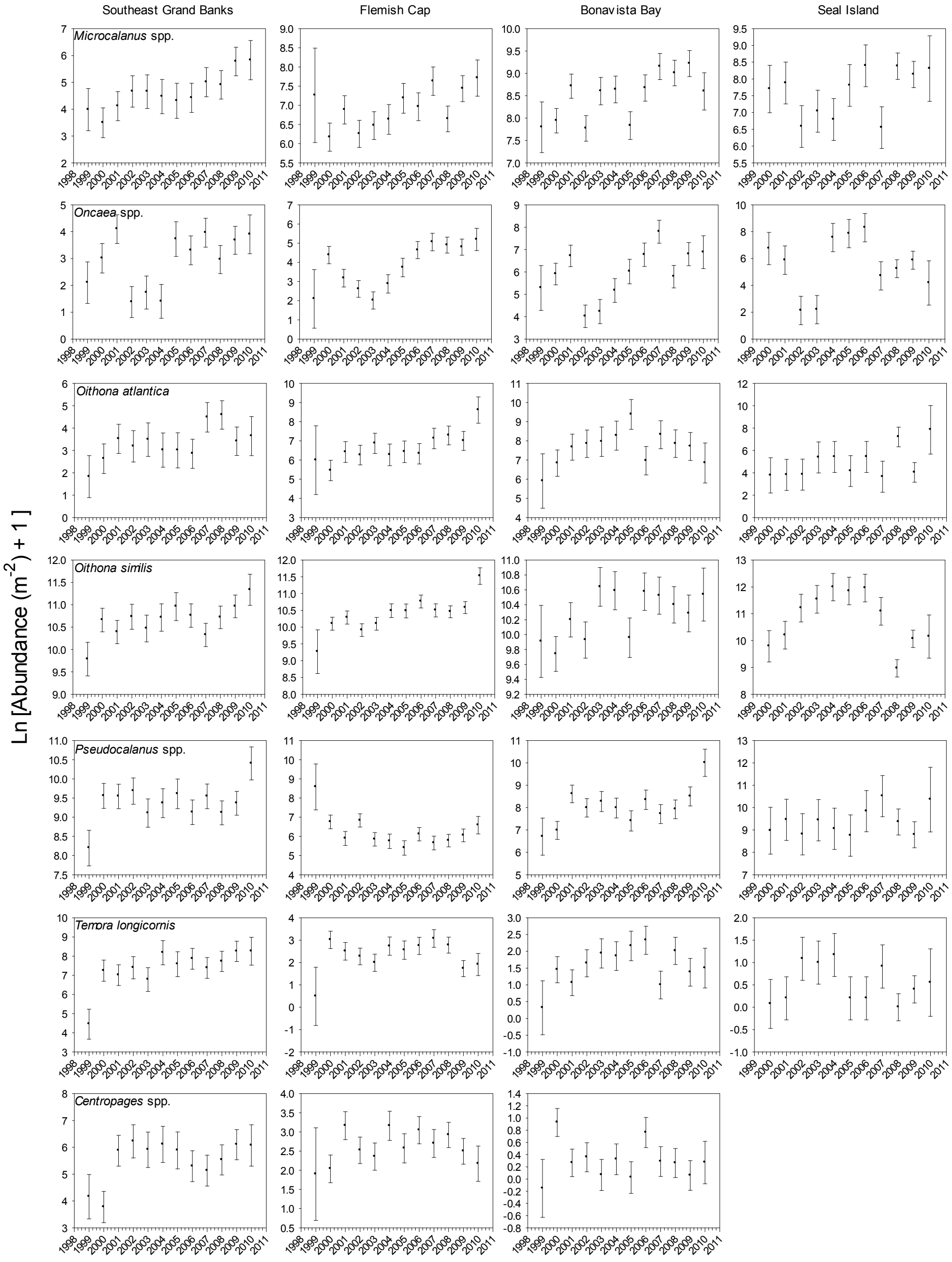


Figure 19. Seasonally-adjusted estimate of the mean abundance of small copepods from the oceanographic transects for the period 1999-2010. The error bars represent standard errors. Values from the Southeast Grand Banks are based on two occupations per year (spring, fall); values from the Flemish Cap and Bonavista sections are based on three occupations per year (spring, summer, fall); values from the Seal Island 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.

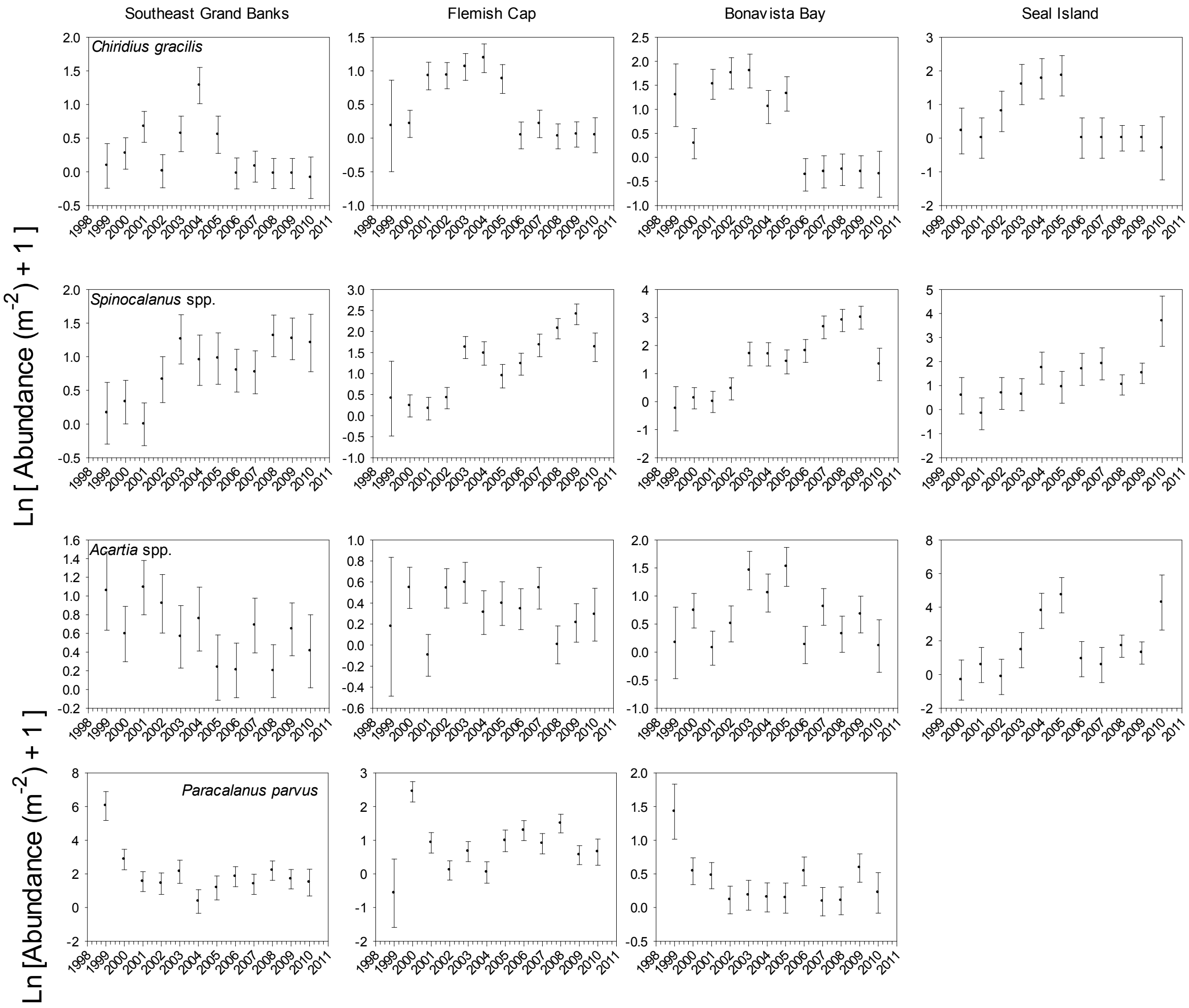


Figure 19. Cont'd.

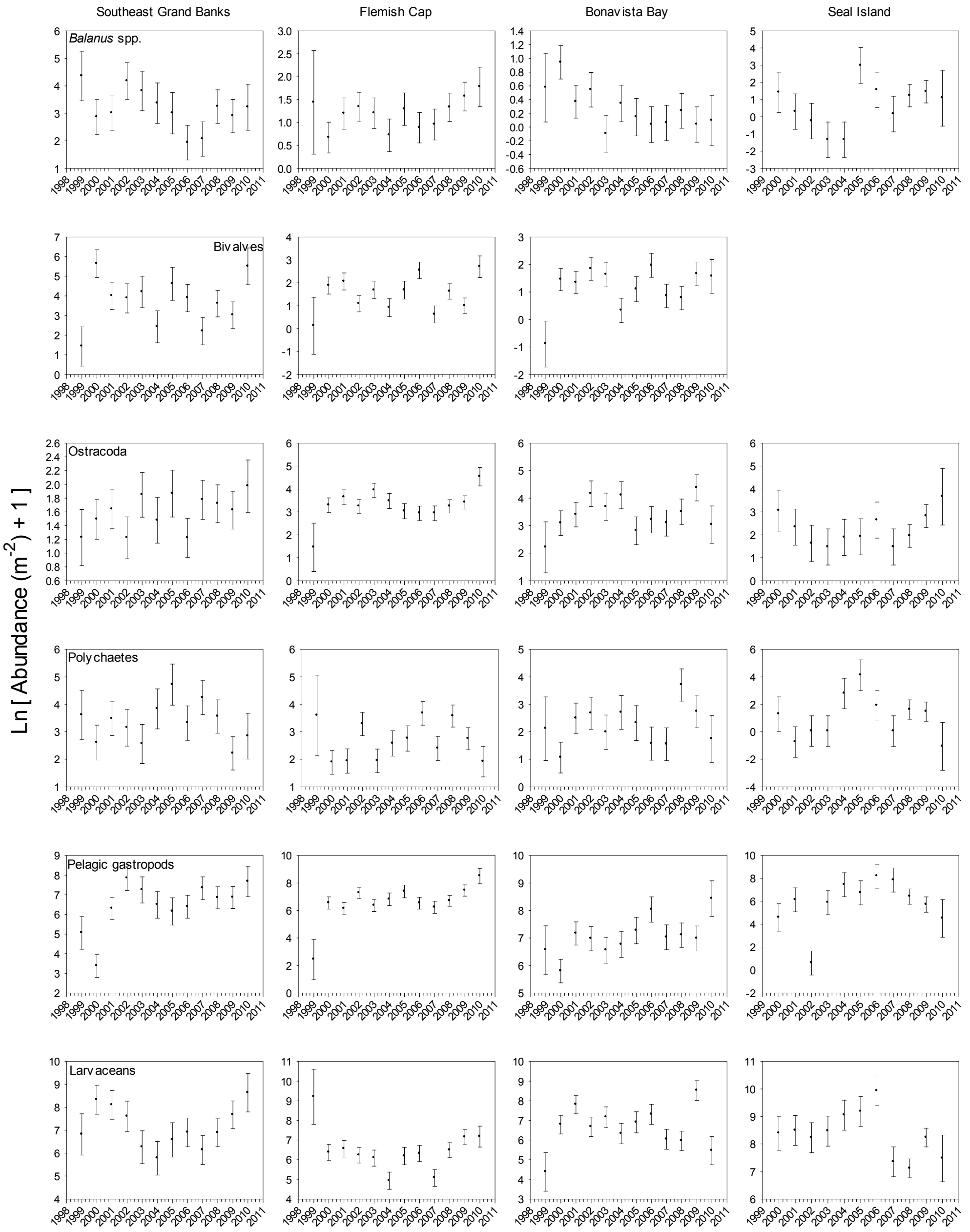


Figure 20. Seasonally-adjusted estimate of the mean abundance of meroplankton from the oceanographic transects for the period 1999-2010. The error bars represent standard errors. Values from the Southeast Grand Banks are based on two occupations per year (spring, fall); values from the Flemish Cap and 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.

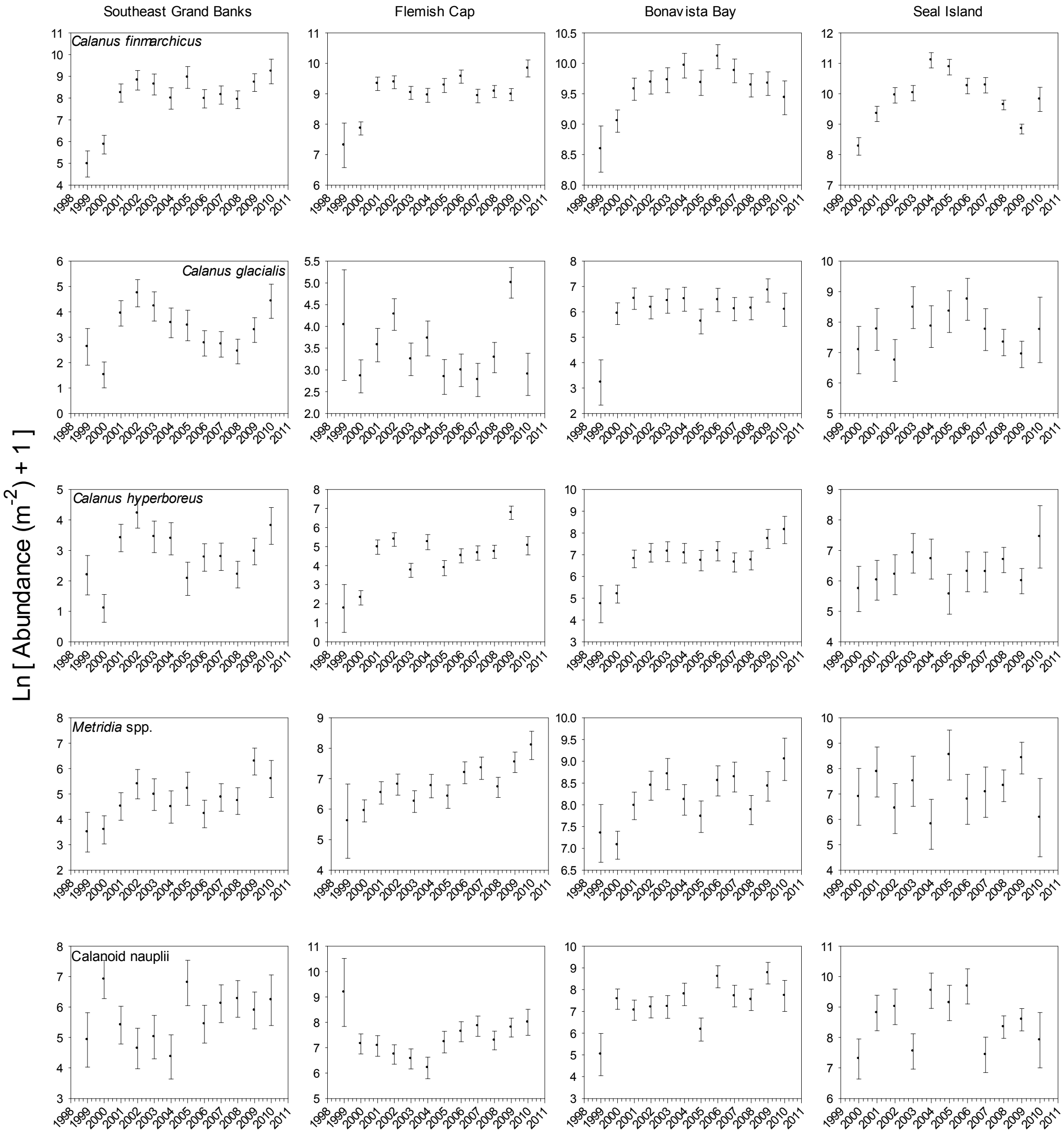


Figure 21. Seasonally-adjusted estimate of the mean abundance of large copepods from the oceanographic transects for the period 1999-2010. The error bars represent standard errors. Values from the Southeast Grand Banks are based on two occupations per year (spring, autumn); values from the Flemish Cap 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.

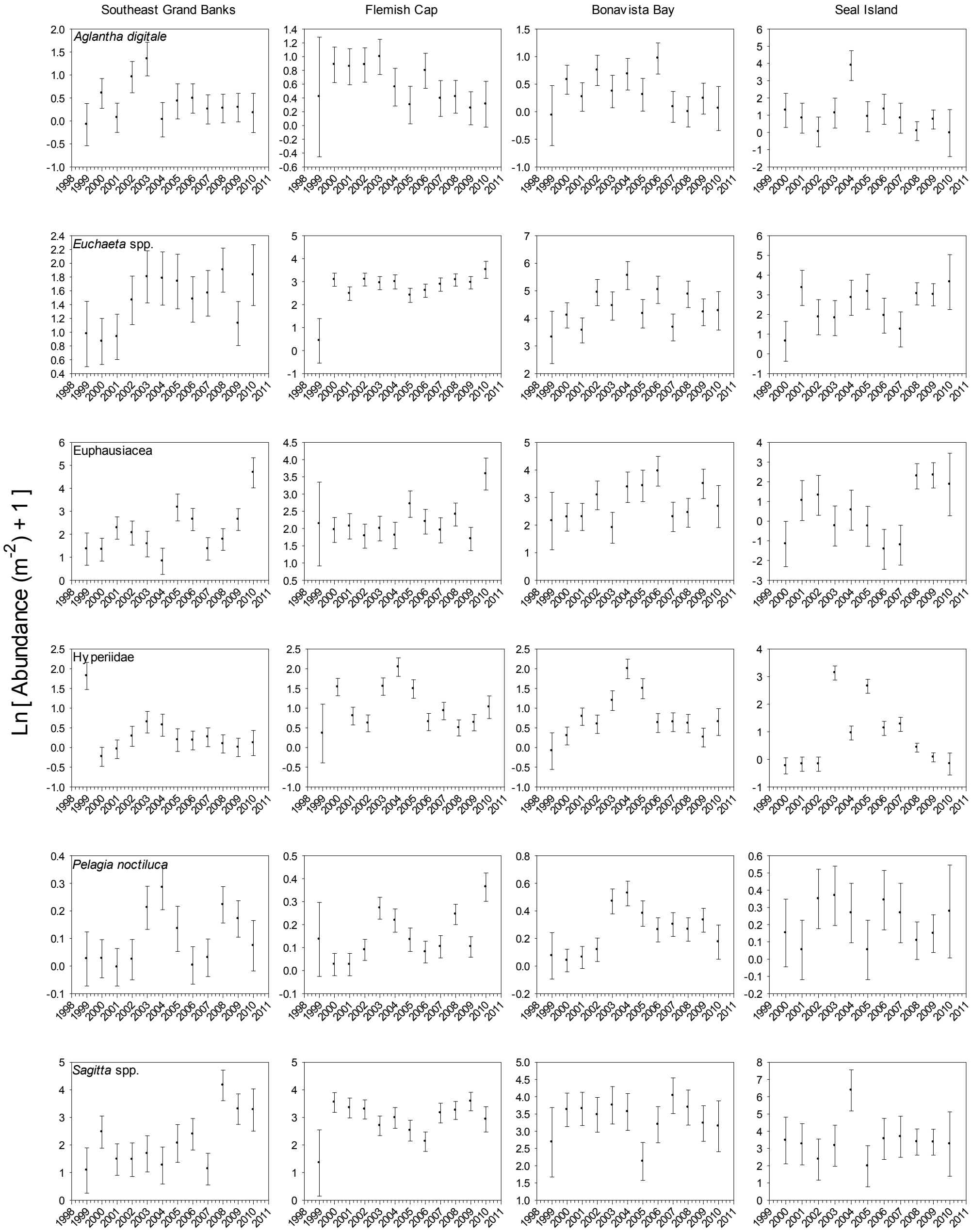
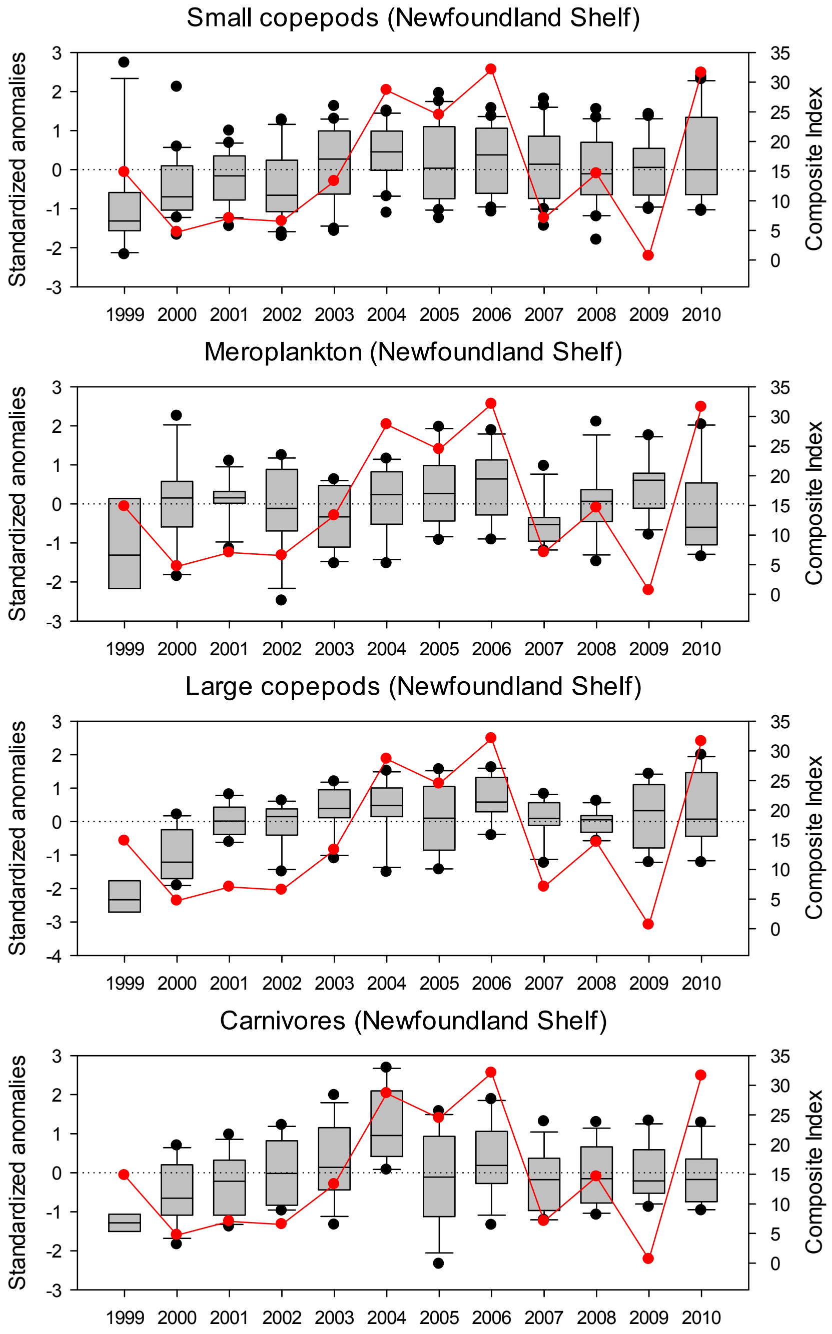


Figure 22. Seasonally-adjusted estimate of the mean abundance of carnivorous zooplankton from the oceanographic transects for the period 1999-2010. The error bars represent standard errors. Values from the Southeast Grand Banks are based on two occupations per year (spring, fall); values from the Flemish 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.


Small copepods (Newfoundland Shelf)

Meroplankton (Newfoundland Shelf)

Large copepods (Newfoundland Shelf)

Carnivores (Newfoundland Shelf)

Figure 23. Box-whisker plots of the standardized anomaly (1999–2010) time-series of the abundance of four functional groups of zooplankton shown in Figures 19–22 from the Bonavista and Seal Island sections (northern ecoregion). The red line represents the composite index of physical oceanographic conditions in the Newfoundland region.

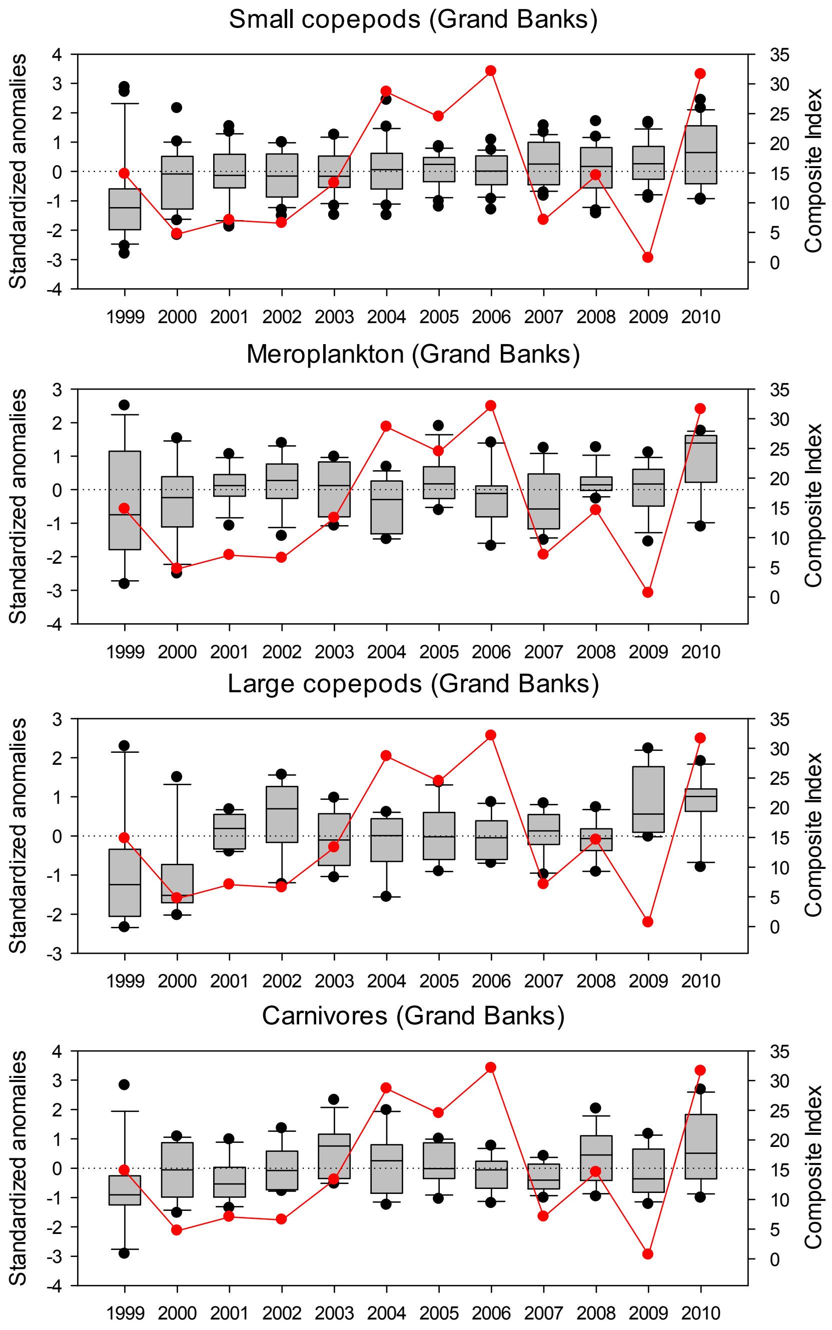
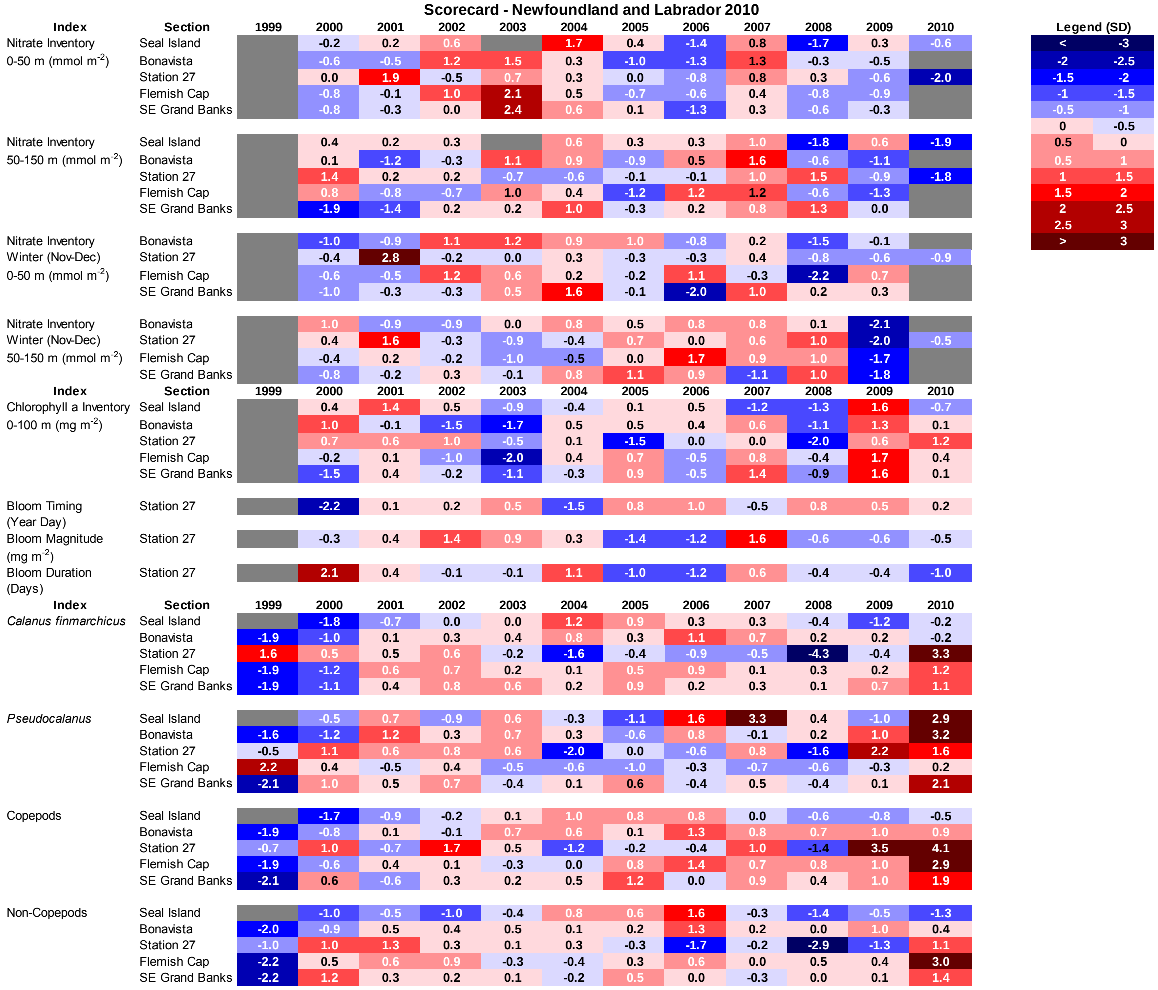


Figure 23. Box-whisker plots of the standardized anomaly (1999–2010) time-series of the abundance of four functional groups of zooplankton shown in Figures 19–22 from the Flemish Cap and southeast Grand Banks sections (southern ecoregion). The red line represents the composite index of physical oceanographic conditions in the Newfoundland region.



Scorecard - Newfoundland and Labrador 2010

Index	Section	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Nitrate Inventory	Seal Island		-0.2	0.2	0.6		1.7	0.4	-1.4	0.8	-1.7	0.3	-0.6
0-50 m (mmol m^{-2})	Bonavista		-0.6	-0.5	1.2	1.5	0.3	-1.0	-1.3	1.3	-0.3	-0.5	
	Station 27		0.0	1.9	-0.5	0.7	0.3	0.0	-0.8	0.8	0.3	-0.6	-2.0
	Flemish Cap		-0.8	-0.1	1.0	2.1	0.5	-0.7	-0.6	0.4	-0.8	-0.9	
	SE Grand Banks		-0.8	-0.3	0.0	2.4	0.6	0.1	-1.3	0.3	-0.6	-0.3	
Nitrate Inventory	Seal Island		0.4	0.2	0.3		0.6	0.3	0.3	1.0	-1.8	0.6	-1.9
50-150 m (mmol m^{-2})	Bonavista		0.1	-1.2	-0.3	1.1	0.9	-0.9	0.5	1.6	-0.6	-1.1	
	Station 27		1.4	0.2	0.2	-0.7	-0.6	-0.1	-0.1	1.0	1.5	-0.9	-1.8
	Flemish Cap		0.8	-0.8	-0.7	1.0	0.4	-1.2	1.2	1.2	-0.6	-1.3	
	SE Grand Banks		-1.9	-1.4	0.2	0.2	1.0	-0.3	0.2	0.8	1.3	0.0	
Nitrate Inventory	Bonavista		-1.0	-0.9	1.1	1.2	0.9	1.0	-0.8	0.2	-1.5	-0.1	
Winter (Nov-Dec)	Station 27		-0.4	2.8	-0.2	0.0	0.3	-0.3	-0.3	0.4	-0.8	-0.6	-0.9
0-50 m (mmol m^{-2})	Flemish Cap		-0.6	-0.5	1.2	0.6	0.2	-0.2	1.1	-0.3	-2.2	0.7	
	SE Grand Banks		-1.0	-0.3	-0.3	0.5	1.6	-0.1	-2.0	1.0	0.2	0.3	
Nitrate Inventory	Bonavista		1.0	-0.9	-0.9	0.0	0.8	0.5	0.8	0.8	0.1	-2.1	
Winter (Nov-Dec)	Station 27		0.4	1.6	-0.3	-0.9	-0.4	0.7	0.0	0.6	1.0	-2.0	-0.5
50-150 m (mmol m^{-2})	Flemish Cap		-0.4	0.2	-0.2	-1.0	-0.5	0.0	1.7	0.9	1.0	-1.7	
	SE Grand Banks		-0.8	-0.2	0.3	-0.1	0.8	1.1	0.9	-1.1	1.0	-1.8	
Index	**Section**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Chlorophyll a Inventory	Seal Island		0.4	1.4	0.5	-0.9	-0.4	0.1	0.5	-1.2	-1.3	1.6	-0.7
0-100 m (mg m^{-2})	Bonavista		1.0	-0.1	-1.5	-1.7	0.5	0.5	0.4	0.6	-1.1	1.3	0.1
	Station 27		0.7	0.6	1.0	-0.5	0.1	-1.5	0.0	0.0	-2.0	0.6	1.2
	Flemish Cap		-0.2	0.1	-1.0	-2.0	0.4	0.7	-0.5	0.8	-0.4	1.7	0.4
	SE Grand Banks		-1.5	0.4	-0.2	-1.1	-0.3	0.9	-0.5	1.4	-0.9	1.6	0.1
Bloom Timing (Year Day)	Station 27		-2.2	0.1	0.2	0.5	-1.5	0.8	1.0	-0.5	0.8	0.5	0.2
Bloom Magnitude (mg m^{-2})	Station 27		-0.3	0.4	1.4	0.9	0.3	-1.4	-1.2	1.6	-0.6	-0.6	-0.5
Bloom Duration (Days)	Station 27		2.1	0.4	-0.1	-0.1	1.1	-1.0	-1.2	0.6	-0.4	-0.4	-1.0
Index	**Section**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Calanus finmarchicus	Seal Island		-1.8	-0.7	0.0	0.0	1.2	0.9	0.3	0.3	-0.4	-1.2	-0.2
	Bonavista	-1.9	-1.0	0.1	0.3	0.4	0.8	0.3	1.1	0.7	0.2	0.2	-0.2
	Station 27	1.6	0.5	0.5	0.6	-0.2	-1.6	-0.4	-0.9	-0.5	-4.3	-0.4	3.3
	Flemish Cap	-1.9	-1.2	0.6	0.7	0.2	0.1	0.5	0.9	0.1	0.3	0.2	1.2
	SE Grand Banks	-1.9	-1.1	0.4	0.8	0.6	0.2	0.9	0.2	0.3	0.1	0.7	1.1
Pseudocalanus	Seal Island		-0.5	0.7	-0.9	0.6	-0.3	-1.1	1.6	3.3	0.4	-1.0	2.9
	Bonavista	-1.6	-1.2	1.2	0.3	0.7	0.3	-0.6	0.8	-0.1	0.2	1.0	3.2
	Station 27	-0.5	1.1	0.6	0.8	0.6	-2.0	0.0	-0.6	0.8	-1.6	2.2	1.6
	Flemish Cap	2.2	0.4	-0.5	0.4	-0.5	-0.6	-1.0	-0.3	-0.7	-0.6	-0.3	0.2
	SE Grand Banks	-2.1	1.0	0.5	0.7	-0.4	0.1	0.6	-0.4	0.5	-0.4	0.1	2.1
Copepods	Seal Island		-1.7	-0.9	-0.2	0.1	1.0	0.8	0.8	0.0	-0.6	-0.8	-0.5
	Bonavista	-1.9	-0.8	0.1	-0.1	0.7	0.6	0.1	1.3	0.8	0.7	1.0	0.9
	Station 27	-0.7	1.0	-0.7	1.7	0.5	-1.2	-0.2	-0.4	1.0	-1.4	3.5	4.1
	Flemish Cap	-1.9	-0.6	0.4	0.1	-0.3	0.0	0.8	1.4	0.7	0.8	1.0	2.9
	SE Grand Banks	-2.1	0.6	-0.6	0.3	0.2	0.5	1.2	0.0	0.9	0.4	1.0	1.9
Non-Copepods	Seal Island		-1.0	-0.5	-1.0	-0.4	0.8	0.6	1.6	-0.3	-1.4	-0.5	-1.3
	Bonavista	-2.0	-0.9	0.5	0.4	0.5	0.1	0.2	1.3	0.2	0.0	1.0	0.4
	Station 27	-1.0	1.0	1.3	0.3	0.1	0.3	-0.3	-1.7	-0.2	-2.9	-1.3	1.1
	Flemish Cap	-2.2	0.5	0.6	0.9	-0.3	-0.4	0.3	0.6	0.0	0.5	0.4	3.0
	SE Grand Banks	-2.2	1.2	0.3	0.2	0.1	-0.2	0.5	0.0	-0.3	0.0	0.1	1.4

Legend (SD)	
<	-3
-2	-2.5
-1.5	-2
-1	-1.5
-0.5	-1
0	-0.5
0.5	0
0.5	1
1	1.5
1.5	2
2	2.5
2.5	3
>	3

Figure 25. Time-series of nutrient inventories, phytoplankton abundance and bloom characteristics, and zooplankton abundance from AZMP oceanographic sections and S27, 1999–2010. A grey cell indicates missing data. The numbers in the cells standardized anomaly values (differences from the long-term average divided by the standard deviation) from the reference period 1999–2010. A red cell indicates a higher-than-normal level and a blue cell indicates a lower-than-normal level; more intense colours indicate larger anomalies.

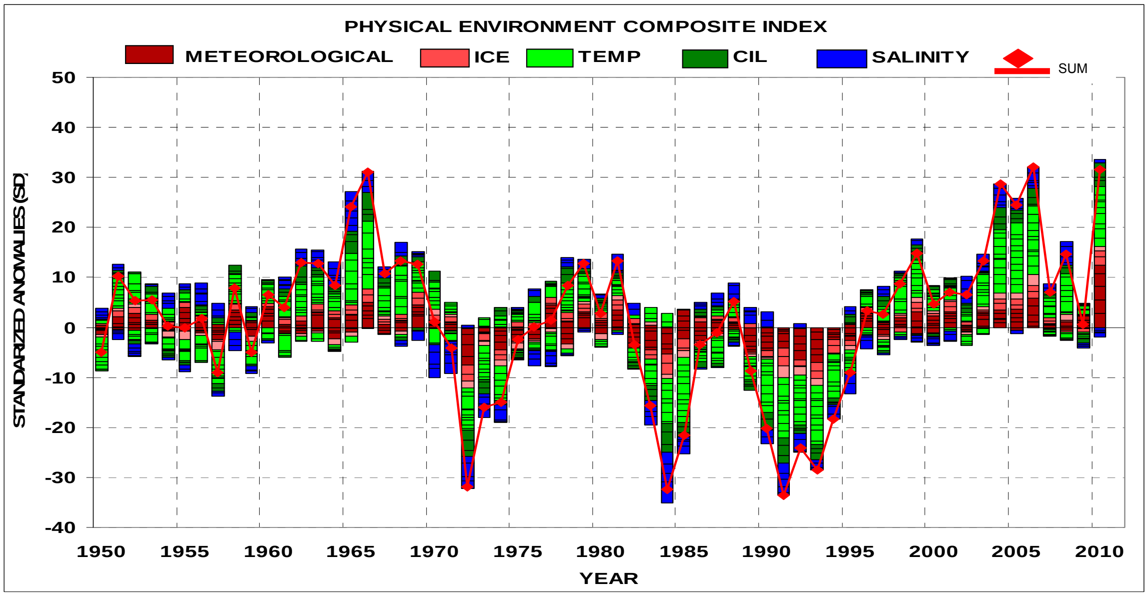


Figure 26. The sum of the anomalies of NAO and air temperature (dark red), ice (dark pink), water temperature (light green), Cold Intermediate Layer (dark green) and salinites (blue) are shown in the bottom panel together with the individual components. The anomalies for each series are normalized with respect to their standard deviations over a base period from 1981 to 2010. Positive anomalies indicate a higher-than-normal level and a negative anomalies indicate a lower-than-normal level.

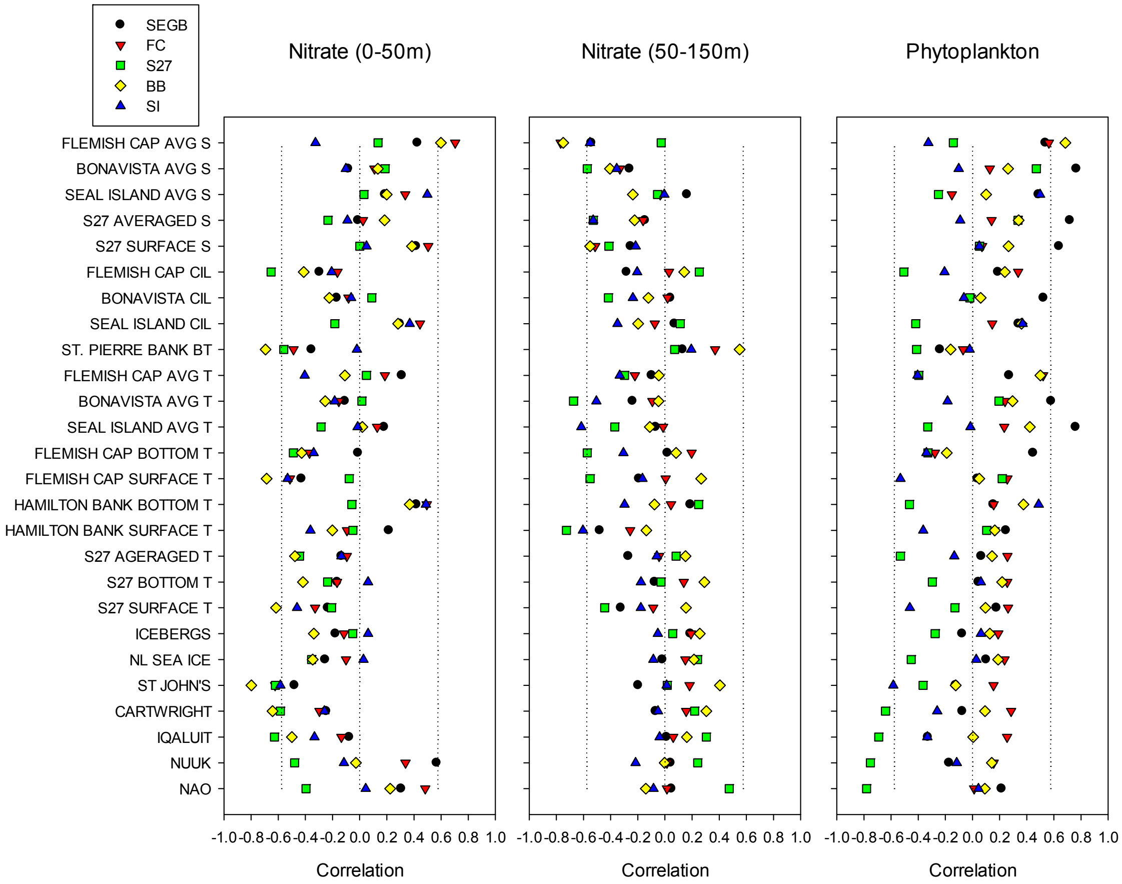


Figure 27. Correlation coefficient of environmental variables with nutrient inventories and estimates of phytoplankton abundance from four oceanographic sections and S27 (see legend in upper left corner). The outer dotted lines represent values of |r | = 0.576, which is statistically significant based on 12 years of observations.

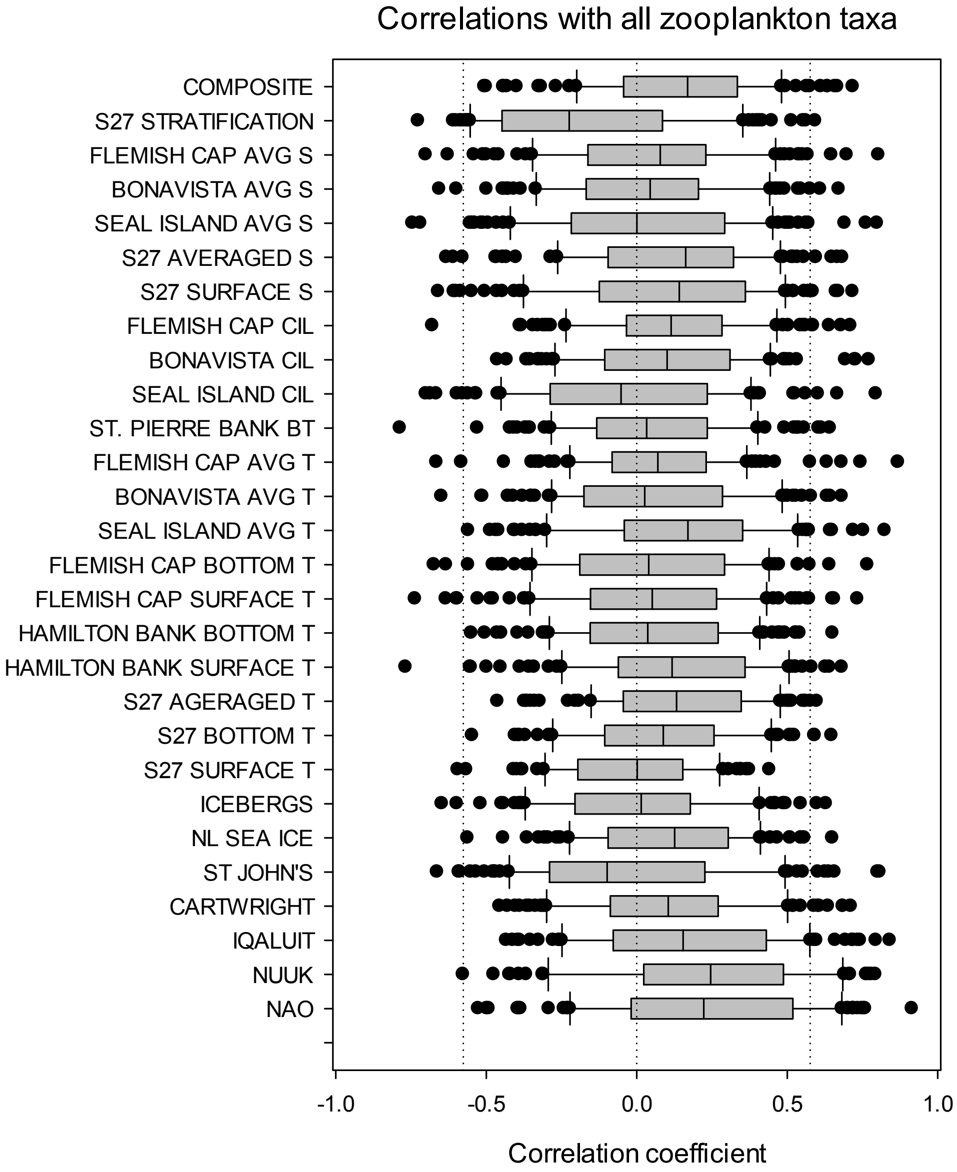


Figure 28. Box-whisker plots of the distribution of Pearson's correlation coefficient of each index of physical environmental variables (y-axis) with all indices of zooplankton abundance (27 taxonomic groups) from each of the four oceanographic sections. Boxes represent the 25th to 75th percentiles of the distribution, with the median contained within. Error bars represent the 5th and 95th percentiles of the distribution and dots represent the outliers beyond those limits. The outer dotted lines represent values of |r| = 0.576, which is statistically significant based on 12 years of observations.

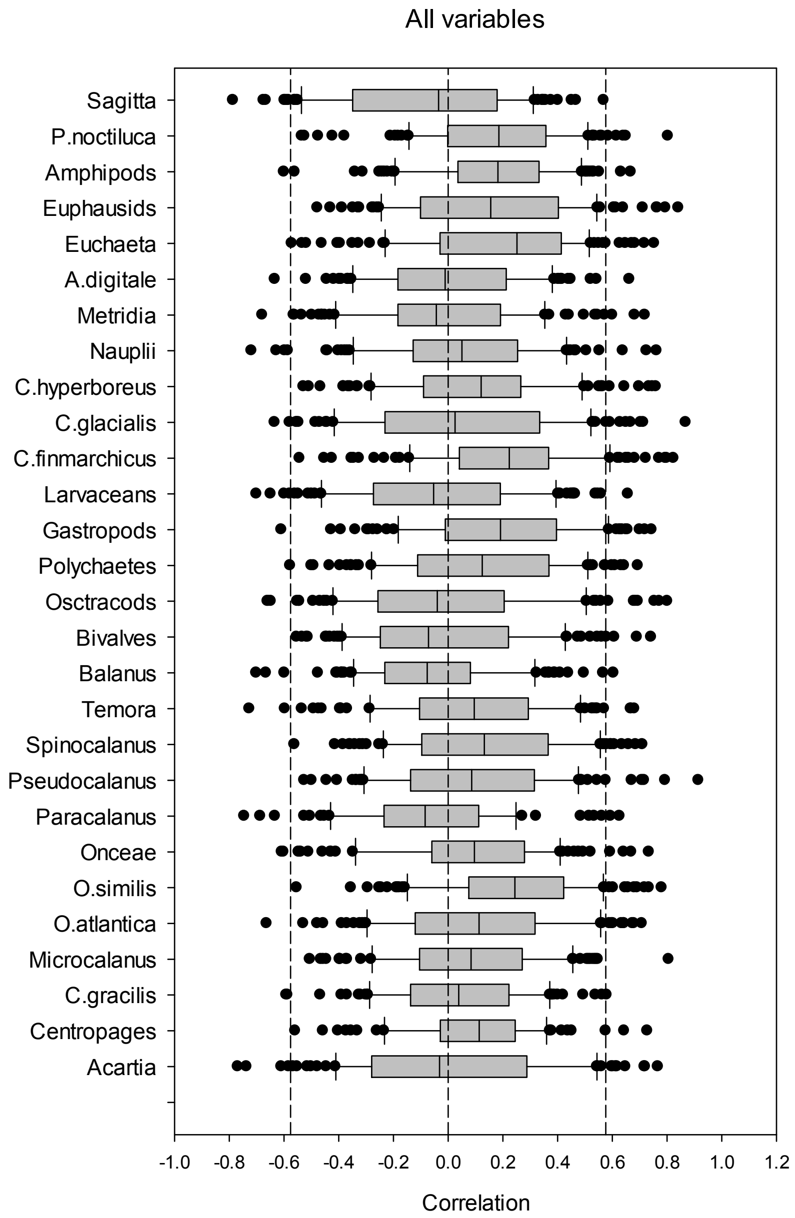


Figure 29. Box-whisker plots of the distribution of Pearson's correlation coefficient of the time-series for the abundance patterns for each zooplankton taxa from all the oceanographic sections (y-axis) with all physical indices (28 variables). Boxes represent the 25th to 75th percentiles of the distribution, with the median contained within. Error bars represent the 5th and 95th percentiles of the distribution and dots represent the outliers beyond those limits. The outer dotted lines represent values of |r| = 0.576, which is statistically significant based on 12 years of observations.