Fisheries and Oceans Canada
Ecosystems and Oceans Science

Pêches et Océans Canada
Sciences des écosystèmes et des océans

Canadian Science Advisory Secretariat (CSAS)

Research Document 2017/009

Newfoundland and Labrador Region

Optical, chemical, and biological oceanographic conditions on the Newfoundland and Labrador Shelf during 2014-2015

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February 2017

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.

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Published by:

Fisheries and Oceans Canada
Canadian Science Advisory Secretariat
200 Kent Street
Ottawa ON K1A 0E6

http://www.dfo-mpo.gc.ca/csas-sccs/
csas-sccs@dfo-mpo.gc.ca

ISSN 1919-5044

Correct citation for this publication:

Pepin, P., Maillet, G., Fraser, S., Doyle, G., Robar, A., Shears, T., and Redmond, G. 2017 Optical, chemical, and biological oceanographic conditions on the Newfoundland and Labrador Shelf during 2014-2015. DFO Can. Sci. Advis. Sec. Res. Doc. 2017/009. v + 37 p.

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ABSTRACT

The cold winters of 2014 and 2015 resulted in colder conditions than had been observed since 2010 which had consequences to the biogeochemical state of the Newfoundland and Labrador (NL) Shelves. Integrated (50 m – bottom) silicate and nitrate inventories recovered somewhat in 2015 relative to the long-term decline that had been observed since at least 2008, although the increase was modest, with the exception of deep nitrate inventories on the Labrador Shelf. Cooler than normal conditions in 2014-15 resulted in a delayed onset of the spring phytoplankton bloom of lower magnitude and reduced integrated chlorophyll concentration, relative to the average, throughout much of the region. The abundances of *Oithona similis, Pseudocalanus* sp. *Temora longicornis* and *Triconia* sp. are at or near record levels of abundance from the Bonavista Bay to the southern Grand Banks sections. In contrast, the abundance of the dominant large copepods (*Calanus finmarchicus*, *Calanus hyperboreus*, and *Calanus glacialis*) has been declining for the last 3-5 years throughout much of the region, although there are local exceptions that have seen an increase for which the cause remains unclear. 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 but some consistency in some trends may be starting to provide new insights into trophic relationships. More comprehensive analyses and modelling are required to understand the drivers of change in productivity on the NL Shelves.

Conditions océanographiques optiques, chimiques, et biologiques sur le Plateau de Terre-Neuve et du Labrador au cours de la période 2014-2015

RÉSUMÉ

Les hivers froids de 2014 et 2015 ont donné lieu à des conditions plus froides que celles observées depuis 2010, ce qui a eu des conséquences sur l'état biogéochimique des plateaux de Terre-Neuve et du Labrador. Les stocks de silicate et de nitrate intégrés (50 m de fond) se sont quelque peu redressés en 2015 par rapport au déclin à long terme observé depuis au moins 2008, bien que l'augmentation ait été modeste, à l'exception des stocks de nitrates profonds sur le plateau du Labrador. Les conditions plus froides que la normale en 2014-15 ont entraîné un début retardé de la floraison printanière du phytoplancton, qui était de plus faible ampleur, et qui a mené à une concentration réduite de chlorophylle intégrée par rapport à la moyenne dans une grande partie de la région. Les abondances d'Oithona similis, *Pseudocalanus spp*. *Temora longicornis* et *Triconia spp*. Sont à des niveaux record d'abondance de la baie de Bonavista jusqu'au Grand Banc. En contraste, l'abondance des copépodes dominants (*Calanus finmarchicus*, *Calanus hyperboreus* et *Calanus glacialis*) a diminué au cours des 3 à 5 dernières années dans une grande partie de la région, bien qu'il y ait des exceptions locales qui ont vu une augmentation dont les causes reste incertaine. Les patrons de variation entre les trois niveaux trophiques étudiés dans ce rapport (sels nutritifs, biomasse phytoplanctonique et abondance du zooplancton) ne révèle aucune association simple entre les niveaux trophiques, mais une certaine cohérence dans certaines tendances commence à fournir de nouvelles connaissances sur les relations trophiques. Une analyse et une modélisation plus complètes sont nécessaires pour comprendre les facteurs de changement de la productivité sur les plateaux de Terre-Neuve et du Labrador.

INTRODUCTION

The Atlantic Zone Monitoring Program (AZMP) was implemented in 1998 with the aim of increasing Fisheries and Oceans Canada's (DFO) 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 (high frequency sampling stations, cross-shelf sections, and groundfish surveys) in each region (Quebec, Gulf, Maritimes, NL) sampled at a frequency of bi-weekly to once annually. The location of the fixed point station and standard sections for the NL region is shown in Figure 1.

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.

This report provides an assessment of the distribution and abundance of macronutrients and plankton on the NL Shelves highlighting the biological oceanographic conditions in 2014-15 but contrasting previous years where information is available. This report complements ocean climate and physical oceanographic assessments of the Region (e.g. Colbourne et al. 2016) and for the Northwest Atlantic shelf system as a whole (DFO 2016).

The water masses characteristic of the NL Shelf are typical dominated by sub-polar waters with a sub-surface temperature range typically below 0°C. Labrador Slope Water flows southward along the shelf edge and into the Flemish Pass, this water mass is generally warmer and saltier than the sub-polar shelf waters. On average bottom temperatures remain <0°C over most of the northern Grand Banks but increase to > 0°C in southern regions and along the slopes of the banks below 200 m. North of the Grand Bank, in Div. 3K, bottom temperatures are generally warmer except for the shallow inshore regions where they are mainly <0°C. Throughout most of the year the cold, relatively fresh water overlying the shelf is separated from the warmer higher-density water of the continental slope region by a strong temperature and density front. This winter-formed water mass is generally referred to as the Cold Intermediate Layer (CIL) and is considered a robust index of ocean climate conditions. In general, shelf water masses undergo seasonal modification in their properties due to the seasonal cycles of air-sea heat flux, wind-forced mixing and ice formation and melt, leading to intense vertical and horizontal gradients particularly along the frontal boundaries separating the shelf and slope water masses.

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 (spring, summer, fall) oceanographic surveys were conducted along standard (primary sections include; Seal Island, Bonavista, Flemish Cap, and southeast Grand Banks) oceanographic sections in the NL region during the 2014-2015 calendar year, in addition to occupations of the fixed coastal station (Station 27 [S27]) during ecosystem trawl surveys (Table 1; Figure 1). A total of 1601/1584 hydrographic station and 244/278 plankton / bottle occupations were conducted in 2014/2015. We achieved near bi-weekly to monthly sampling of S27 during March-December in 2014 with a combined total of 43 hydrographic and biological occupations. We achieved full monthly coverage in 2015 with a combined total of 52 hydrographic and biological occupations. Oceanographic sample collections for S27 and standard sections includes a conductivity, temperature, depth (CTD) high resolution profile using a Sea-Bird Electronics SBE-9plus instrument equipped with dissolved oxygen, chlorophyll fluorescence, photosynthetic active radiation (PAR) and pH sensors, Niskin water bottle samples using a CTD-rosette at standard depths of 5, 10, 20, 30, 40, 50, 75, 100, 150m, and near bottom for calibration of salinity and oxygen, chlorophyll *a* and nutrient analyses. Combined vertical ring net plankton tows to a maximum depth of 1,000 m using a dual-202 µm or 202-70 µm for taxonomic, abundance, and biomass analyses of zooplankton. In addition to the standard discrete water sampling program for biological and chemical conditions, particulate organic carbon and nitrogen and carbonate (total alkalinity and total dissolved inorganic carbon) are routinely collected at a subset of stations and depths but are not reported here.

OPTICAL PROPERTIES AND VERTICALLY INTEGRATED VARIABLES

The vertical attenuation coefficient (K_d) was derived from in-water light extinction measurements using a CTD-rosette mounted PAR 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:

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

where B(z) is the concentration of chlorophyll *a* 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 50 m. 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_chla when $K_{d\text{-}PAR}$ was not available to compute the euphotic depth.

Annual estimates of water column inventories (using trapezoidal numerical integration) of nutrients (0-50 m and 50-150 m), chlorophyll *a* (0-100 m), 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}, α is the intercept, β and δ are categorical effects for year and month effects, and ε is the error, and

$Ln(Density) = \alpha + \beta YEAR + \delta STATION + \gamma SEASON + \varepsilon$

to derive an estimate of the interannual variations based on all occupations of the transects, where δ takes into account the effect of station location and γ 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. Because the model estimates are adjusted annually as a result of the input of new data, *YEAR* effects tend to vary from one assessment to the next but any changes are verified against the raw data to ensure that the underlying spatial (*STATION*) or temporal (*SEASON*) patterns along each section are maintained. Large departures from previous patterns could be indicative of shifts in the dominant regime or ecosystem processes.

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 July 2002 until December 2013 with Sea-viewing Wide Field-of-view Sensor (SeaWiFS) from September 1997 until December 2009 to construct composite time series of surface chlorophyll *a* (CHLA) across 10 statistical sub-regions in NL, extending from Hudson Strait down to the Southeast Shoal (see Figure 2 for locations). Relatively, new ocean colour data is now available from VIIRS (Visible Infrared Imaging Radiometer Suite) satellite which is now becoming available for analysis but has not yet been integrated with earlier time series. Basic statistics (mean, range, standard deviation, etc.) are extracted from two week average composites for selected sub-regions based on SeaWiFS and MODIS. We report on the available time-series of mean surface chlorophyll *a* levels at selected sub-regions on the NL Shelf. Data from both satellite sensors was provided by the Bedford Institute of Oceanography (Carla Caverhill, personal communication) and we computed an average value of surface chlorophyll *a* during the overlap period of the satellites. Data gaps greater than one month in duration were excluded from 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). Four different metrics were computed using satellite composite data during the spring bloom to characterize the integral (magnitude) of chlorophyll *a* concentration under the Gaussian curve (mg m^{-2} d^{-1}), the peak-timing of the spring bloom peak (Julian day), duration of the spring bloom cycle (days) and the peak intensity of the spring bloom.

SCORECARD

Scorecards of key indices, based on normalized, seasonally-adjusted annual anomalies, represent a summary and means to contrast a variety of physical, chemical, and biological variables and observations. A standard set of indices are computed representing anomalies of nutrient availability, phytoplankton biomass and spring bloom dynamics, and the abundance of dominant copepod species and key functional groups (*Calanus finmarchicus*, *Pseudocalanus* spp., total copepods, and total non-copepods are produced throughout the Atlantic zone. To visualize the Northwest Atlantic shelf scale patterns of environmental information, a zonal scorecard was prepared in addition to the regional scorecards presented in this document (DFO 2016).

OBSERVATIONS

OPTICAL AND BIOLOGICAL PROPERTIES – FIXED STATION

The seasonal development of optical and chlorophyll a indices at S27 continue to indicate changes in phytoplankton biomass and phenology of the production cycle that have been noted in previous years (Figure 3). Both optical and chlorophyll a indices indicated a reduction in the integrated biomass and delayed onset and duration of the spring bloom in 2014-15 in contrast to average conditions observed in previous years. The optical data closely match the pattern observed in 0-100 m integrated chlorophyll a index based on extracted pigment (Figure 3). Short-term episodic summer and autumn blooms are detected via optical data but do not necessarily match the observed temporal changes in chlorophyll a biomass measured during these respective time periods.

NUTRIENTS AND PHYTOPLANKTON – FIXED STATION AND SECTIONS

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 inventories. The inventories of nutrients are strongly influenced by seasonal biological processes operating throughout the upper water-column. In general, the shallow (upper 50 m) inventories of both silicate and nitrate at S27 show some signs of earlier and more extensive depletion since 2006 (Figure 4). The timing in reduction of shallow nutrient inventories normally coincides closely with the timing of the spring bloom based on optical and biochemical indices (Figure 3). In addition, episodic renewal during summer and replenishment of nitrate in the late autumn appears to be limited or delayed in contrast to previous observations (Figure 4). Substantial variability in the evolution of deep inventories of silicate and nitrate has also been noted over the last two decades. Reductions in deep inventories of nutrients have been observed prior to the spring bloom indicating source inputs may have changed (Figure 4). Additional depletion of nutrients, in particular deep silicate inventories in late spring, have been observed to reach < 200 mmol m^{-2} that was first detected in 2004 and remain ongoing. The replenishment of silicate and nitrate levels in the deep strata that typically occurs in the early to late autumn has undergone further reduction and more deplete in nitrate compared to silicate inventories (Figure 4).

Comparison of mean conditions in vertical structure and annual variability in inventories of nutrients and chlorophyll during 1999-2010 reveal characteristic features of drawdown in near-surface waters in silicate and nitrate from high winter > 3 mmol m^{-3} (~ 200 mmol m^{-2}) levels to < 1mmol m^{-3} by early April which coincides with the onset of the spring phytoplankton bloom and renewal of surface concentrations in late autumn (Figs. 5 and 6). Inventories of macro nutrients reach < 50 mmol m^{-2} by June and then begin to increase gradually throughout the autumn period. Reduction in silicate concentrations occurs later in spring-early summer and the drawdown is not as extensive as observed in nitrate concentrations. Chlorophyll *a* concentrations and inventories within the upper 100 m begin to increase above background levels starting in early winter and peak normally in April before reaching background levels again by early June (Figs. 5 and 6). The absence of observations during the early part of 2014 precluded an evaluation of the exact timing of drawdown in nutrients which appeared to be earlier and significantly greater in terms of silicate depletion relative to nitrate, similar to the standard reference period (Figs. 5 and 6). The extensive drawdown in silicate did not translate into a more extensive spring bloom in 2014, which was considerably weaker compared to the reference period (Figs. 5 and 6). Nutrient concentrations throughout the water column increased in 2015 compared to the previous year and although the spring bloom was comparable in terms of intensity, both the vertical extent, initiation and duration were somewhat limited in contrast to the reference period.

A summary of annual anomalies of chlorophyll and nutrient inventories from the standard Sections and S27 during 2014-15 are shown in Figure 7. In general, the 2014 anomaly for chlorophyll was below normal with the exception of the southeast Grand Bank at well below (> 2 standard deviations [SD]) the 1999-2010 average (standard climatology). The 2014 anomalies for silicate inventories in the shallow (0-50 m integral) layer were generally 1-2 SD below normal in contrast to nitrate that was near normal with the exception of S27 and southeast Grand Bank with depleted levels (Figure 7). Shallow inventories of silicate were more depleted on the Grand Bank compared to northern sections. We continued to observe substantial reductions in deep (> 50 m integral) inventories of silicate and nitrate in 2014 (Figs. 6 and 7). The nutrient inventories in the deep layer were substantially reduced approaching 2.5 SD below normal compared to the long-term climatology. The southeast Grand Bank section was the only exception with deep inventories of silicate and nitrate only slightly below normal in 2014. This pattern has also been observed in previous years with higher levels of depletion along the northern sections while moderating southwards. The anomalies of integrated chlorophyll in the upper 100 m continue to remain at lower levels in 2015 approaching nearly 3 SD below normal along the Grand Bank Sections (Figure 7). Mostly positive anomalies are noted for the shallow nutrient inventories and some signs of increasing levels of deep inventories of silicate and nitrate in 2015, particularly along the northeast Newfoundland Shelf compared to the previous year (Figure 7). Despite the higher levels of nutrient inventories observed along the northern Sections in 2015, deep nutrient inventories continue to remain depleted compared to the long-term climatology on the Grand Bank.

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. The phytoplankton and nutrient variables examined show some short-term coherent trends and transition periods during the 17-year time series. Phytoplankton biomass inferred from chlorophyll *a* peaked in the early part of the time series but remained relatively stable throughout the 2000s (Figure 8). Since 2011, phytoplankton biomass has remained mostly below normal through to 2015. In general, shallow and deep inventories of silicate and nitrate declined well below normal coincident with the decrease in phytoplankton observed in 2011 and remain ongoing through 2014. In general, shallow inventories of silicate and nitrate increased in 2015 above normal compared to the reference period along the standard sections (Figure 8). Although, the deep (> 50 m) layer inventories of silicate and nitrate remain lower in recent years, levels have improved from 2-3 SD units observed in 2013-14 to ~ 1-2 SD below normal in 2015 (Figure 8). Although the cause for the observed transition to lower shallow and deep macro-nutrient inventories in recent years is currently unknown, the lower levels may be in part contribute to the observed changes in timing and intensity of the spring bloom throughout the NL region.

To examine trends over the northern and southern areas, we computed composite summed annual anomalies across the Labrador and NE Newfoundland Shelf (northern) and Grand Bank including Flemish Cap (southern). The composite inventories of integrated chlorophyll a and macronutrients were relatively coherent across the southern Labrador and northeast Newfoundland Shelf and Grand Bank (Figure 9). No distinct trend is observed in the integrated chlorophyll time series other than consistent negative anomalies ongoing since 2010. The shallow inventories for both silicate and nitrate are relatively stable through time although appear to be out of phase between northern and southern sections in recent years (Figure 9). A clear overall downward trend is evident in both of the deep nutrient inventories although, the deep nitrate time series shows some sign of return to normal levels along the northern sections (Figure 9). The downward trend in deep composite silicate levels has been more gradual over the time series in contrast to deep nitrate showing an abrupt decline from 2007-08 onward.

REMOTE SENSING OF OCEAN COLOUR

Satellite ocean colour (MODIS) data provides a large-scale perspective of surface phytoplankton biomass (chlorophyll *a*) over the whole of the NW Atlantic that is not possible for conventional vessel-based sampling. Using two-week satellite composite images of sub-regions supplements our ship-based observations and provides seasonal coverage and a large-scale context with which to interpret our survey data. 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 occurred on the south-western areas of the Grand Banks and Flemish Cap by late April 2014-15 (see Figure 10). The spring bloom gradually intensified over the eastern half of the Grand Bank and northeast Newfoundland Shelf by early May, with chlorophyll *a* concentrations in excess of 10 mg m^{-3} (imagery not shown). Given the delay in timing of the spring bloom observed in 2014 and 2015 compared to our normal survey timing in April, indicates that we missed a significant portion of surface blooms along the standard sections. During the 2014-15 summer oceanographic survey, near surface concentrations of chlorophyll *a* were at background levels (~ 1mg m^{-3}) over much of the northwest Atlantic, with the exception of the southern coastal zone along the Labrador Shelf and Labrador Sea where concentrations reached 2-3 mg m^{-3} (Figure 10). Extensive cloud cover during the autumn survey in 2014-15 in late November limited our capacity to detect the areal extent of surface blooms except for the southern Grand Bank (Figure 10).

At larger scales, observations from 10 statistical sub-regions ranging from the Hudson Strait in northern Labrador to the southeast Shoal on the Grand Bank reveals the associated changes in the timing and intensity of spring and autumn blooms during recent years (2012-15) as detected by VIIRS ocean colour imagery (Figure 11). The northern regions are characterized by reduced intensity and later bloom timing but longer duration compared to a more intense spring bloom along the southern Labrador and Newfoundland Shelf that propagates earlier and generally becomes more intense towards the southeast Shoal. Despite the limited number of years of VIIRS ocean colour data, shifts in timing are apparent with delayed onset of the spring bloom across the southern Labrador and northeast Shelf, and northern portion of the Grand Bank during the short time series (Figure 11). This trend is less apparent in northern Labrador, Flemish Pass and Cap, as well as the southeast Shoal. The occurrence of autumn blooms, which is sometimes not captured well by conventional sampling, was supported by the high-resolution VIIRS imagery across all statistical sub-regions with the exception of the Hudson Strait that exhibits a near continuous production cycle from early summer through until the autumn (Figure 11). The short time series does suggest some associated changes in the extent and timing of autumn blooms but is difficult to quantify given the reduced concentrations of chlorophyll a that are only slightly higher than background levels.

A number of different metrics derived from satellite imagery using combined SeaWiFS and MODIS imagery were examined to characterize the 2014-15 annual anomalies for the extent (magnitude and amplitude) and timing (peak timing and duration) indices of the spring bloom. Data was insufficient in the northern regions (Labrador Shelf) which did not permit parameter fitting and estimation of the different metrics. Overall, the amplitude (peak intensity) and magnitude (integrated chlorophyll *a* biomass) of the spring bloom was below normal across most of the NL sub-regions in 2014-15 compared to the standard reference period (1998-2010). The only exceptions were observed on the northeast Shelf with above average amplitude of the spring peak (Figure 12). Peak timing of the spring bloom was substantially delayed with large positive anomalies from the northeast Newfoundland Shelf and Grand Bank although closer to normal on the Flemish Pass and Cap (Figure 12).

The standardized scorecard anomalies derived from many of the ocean colour metrics showed relatively high spatial and temporal variability across the statistical NL sub-regions during the time series although some coherent trends are becoming apparent (Figs. 13 and 14). In general, larger numbers of > 1 SD positive anomalies in the magnitude and amplitude of the spring bloom were observed during the late 2000's (in some cases reaching up to 3-4 SD) with transition to mostly negative anomalies in 2012-2015 (Figure 13). Coherent shifts in timing indices of the spring bloom have also been noted across the NL statistical sub-regions. Short-term transitions of 2-3 years between early versus delayed onset of the spring bloom have been observed (e.g. 2001-03 and 2014-15 delayed; 2005-06 and 2009-10 early cycles) (Figure 14).

To examine for trends over larger areas, we computed composite summed annual anomalies across the Labrador and NE Newfoundland Shelf, Flemish Pass and Cap, and the Grand Bank sub-regions. The composite time series show high interannual variability across the different metrics along with short-term (3-5 years) trends (Figure 15). In general, the magnitude and amplitude of the spring bloom remained near normal during the first-half of the time series but transitioned to higher levels throughout 2008-11 but have since declined below the reference mean during recent years. Changes in peak timing of the spring bloom appear to be coherent across the region indicate a potential broad-scale synoptic response (Figure 15). Again, no overall trend is apparent in peak timing during the 18-year time series. The duration of the spring bloom appear to show somewhat larger differences across the combined areas and short-term trends. The mostly negative composite anomalies observed since 2011 and ongoing indicate reduced duration of the production cycle across the NL Shelf (Figure 15).

TRENDS ON OCEANOGRAPHIC SECTIONS – ZOOPLANKTON

Small copepods (Figure 16) – species that contribute to this group can be separated into two categories: those that have shown a general increase in abundance during the period 1999-2013, 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., *Triconia* sp., *Oithona atlantica*, *Oithona similis*, *Centropages* sp., and *Spinocalanus* sp. have shown generally positive trends during the last decade, although *Microcalanus* sp. has declined somewhat on the southeastern Grand Banks section since 2012. *Pseudocalanus* sp. and *Triconia* sp., and *Temora longicornis* have demonstrated considerable increases in abundance during the last 3-5 years on the southeast Grand Banks and Flemish Cap sections. We have stopped reporting trends in the abundance of *Chiridius gracilis*, and *Acartia* sp. because of data limitations. *Paracalanus parvus* has all been at low levels in recent years, following a long term declining trend. Positive trends in the abundance of small copepods were strongest on the southeast Grand Banks and Flemish Cap sections whereas abundance levels in the last 5-10 years on the Bonavista Bay and Seal Island sections have either shown no notable trend or demonstrated a decline.

Large copepods (Figure 17) – *Calanus finmarchicus* is numerically dominant among the species of large copepods in the region. The abundance of this keystone species in the Newfoundland and Labrador ecosystems has demonstrated a general decline in abundance during the last five years on the southeast Grand Banks and Flemish Cap sections while there has been a general decline over the last ten years on the Bonavista Bay and Seal Island sections. The magnitude of the decline has been much more pronounced on the southeast Grand Banks section, although the overall abundance of this species throughout the region remains above the record low levels encountered in 1999-2000.

Calanus glacialis is a cold water species that occurs principally over the continental shelf. It is most abundant on the Seal Island section. Abundance on the southeast Grand Banks section has shown a general decline since 2002 to reach the second lowest level on record in 2015 despite short term fluctuations from year to year. In 2014-15, there was a notable increase in abundance on the Flemish Cap section, a pattern that was mirrored on the Seal Island section as well. Abundance of this species on the Bonavista section has shown very limited inter-annual variability although abundance peaked in 2010 and densities from 2013-15 have been generally high.

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 to reach a near record low level in 2015. Although variable in abundance on the Flemish Cap section, abundance has generally declined since 2010. The trend in the northern ecoregion had been toward an increase from 1999 to 2003 after which interannual variations have been limited although there are suggestions of a general decline on the Bonavista section since ~2009.

Metridia sp. (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 was a general increase in abundance along the Grand Banks (although still below peak densities of 2009), while on the Flemish Cap and Bonavista sections there has been a general declining trend since 2009-10.

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 and production by a number of species. However, it is noteworthy that the overall abundance of this group had declined approximately 25-fold in 2015 relative to densities encountered in 2009 on the southeast Grand Banks section.

Meroplankton (larval stages of *Balanus* sp., bivalves and polychaetes) and other selected taxa (Figure 18) 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 had been a long-term decline in the abundance of *Balanus* sp. on the Grand Banks section from 1999-2012 but this trend was reversed from 2013 onward to reach maximum densities in 2015; there was an increase on the Flemish Cap section from 2010 to 2014 with a sharp decline in 2015; and there has been a general decline on both the Bonavista and Seal Island sections since 2010. Other meroplankton have not exhibited anything more than short-term and localized trends although abundance of polychaetes has been at record levels on the Grand Banks and Flemish Cap sections since 2012. Ostracods have generally shown an increasing trend in the southern ecoregion since the inception of AZMP but have been declining in the northern ecoregion since 2009. The abundance of pelagic gastropods declined substantially in 2011 along the Grand Banks, Flemish Cap and Bonavista sections with some recovery apparent on all three sections since then. Abundance on the Seal Island section remained low since 2006 but reached record densities in 2015. The density of larvaceans has been highly variable from year-to-year but abundance levels were generally high in 2014-15, with the exception of the southeast Grand Banks section.

Carnivorous zooplankton (Figure 19) – 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 2003-06 although the abundance of the former reached record or near record levels in 2014-2015 on the southeast Grand Banks and Flemish Cap sections. Hyperiid amphipods have been relatively stable on the Grand Banks and Seal Island sections but their abundance has increased steadily since 2011-12 on the Flemish Cap and Bonavista Bay sections to reach record levels in 2015. In contrast, the abundance of euphausiids (largely juveniles) which had generally increased since the inception of the sampling program declined in abundance in 2014-15 on all but the Seal Island section. Abundance of *Euchaeta* sp. and *Sagitta* sp. has been highly variable among sections.

TRENDS – TIME SERIES DATA FROM S27

The high frequency sampling site S27 provides 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 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).

Copepod biomass, based on copepodite and adult 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*), declined from the high levels measured in 2009 and reached the lowest value on record in 2013; biomass levels recovered somewhat in 2014-15 to average levels (Figure 20). All three species of *Calanus* along with calanoid nauplii, *Metridia* sp. have generally been in decline since 2009 although *Calanus glacialis* abundance increased in 2015. Small copepods (*Oithona* sp., *Pseudocalanus* sp., *Temora longicornis* and *Microcalanus* sp.) were generally at record levels in 2015 following a general declining trend after their peak abundance in 2009 or 2010 (Figure 21). The abundance of *Triconia* sp., larvaceans and pelagic gastropods was generally high in 2014-15. Many taxa from S27 appear to show a general oscillation over the course of 1999-2015 but there is no dominant and consistent pattern of variation among taxa.

COPEPOD PHENOLOGY

Previous reports (e.g. Pepin et al. 2011*a*) have noted a high degree of consistency in the general seasonal succession of stages of *C. finmarchicus* and *Pseudocalanus* sp. 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 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 (Pepin et al. 2015). 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. The occurrence of stage I copepodites (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. (1986) estimates of food-saturated temperature-dependent development times based on 0-25 m 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.

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 2005-06, when the fall cohort increases in prominence (Figure 22). 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 have declined in relative abundance and reaches a peak earlier in the year than during the period 1999-2006 but the importance of this cohort of adults increased once again in 2012 onward. The changes in phenology of late stage copepodites are somewhat apparent in the earlier occurrence of CIII-CIV copepodite stages both in the winter and in their earlier occurrence in June-July.

The seasonal succession of *Pseudocalanus* sp. has a substantial cohort of CV copepodites from January to March which is closely followed by a peak in the abundance of CVI adults (Figure 23). CI and CII copepodites are abundant from April to August and May 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 in August or September, but it was not until 2005 or 2006 that a second cohort of CVI adults began to appear in June and July. The shift in phenology of *Pseudocalanus* sp. is somewhat more dramatic than that of *C. finmarchicus* because the winter cohort of CVs appears to be to 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 followed by an earlier occurrence of CI copepodites starting in 2011.

DISCUSSION

There are a number of emerging trends in oceanographic conditions in the region. Data from the high frequency sampling station (S27) indicate that physical habitat indices have gradually shifted in recent years toward warmer winters, greater persistence of a deeper mixed layer during the spring, and lower salinity in the fall that may affect the occurrence of fall phytoplankton blooms. Warmer winter conditions may affect phytoplankton in two ways by allowing higher background biomass levels to persist through the winter but also by affecting the development of key copepod species. We have noted earlier occurrence of adults and sub-adult copepodites for both *Calanus finmarchicus* and *Pseudocalanus* sp. In the case of the former, preliminary estimates of winter development rates suggest that the slight winter warming may be sufficient to result in the earlier occurrence of adult females (Pepin, unpublished data). Greater persistence of a deep mixed layer in the spring may be affecting the duration of the spring phytoplankton bloom, which has shortened in duration dramatically from 2000 to 2013 although the timing of the spring bloom was delayed in 2014 and 2015, a pattern which is consistent with the broader scale signal identified from remote sensing of surface chlorophyll biomass. These changes are also coupled with some notable trends in the surface and bottom inventories of silicate and nitrate. If these combined trends persist they may have impacts on the regional production potential but we have to be cautious in extrapolating the results on a regional scale because of the high degree of equatorward transport that dominates regional circulation.

At S27, many of the most abundant zooplankton taxa have been showing a decline in abundance over the last 3 to 5 years with a net result that the estimated copepod biomass reached a record low level in 2013 but has recovered to the long-term average in 2014-15, a pattern that is consistent with overall measured biomass. In contrast, the abundance of some key small copepods (*Oithona similis*, *Pseudocalanus* sp.) appeared to be at or near record levels along some oceanographic sections. In contrast, the abundance of large copepods has been more variable, with *C. finmarchicus* and *C. hyperboreus* showing declining abundance trends in the last five years to reach density levels that are either average or well below average. In contrast, the abundance of *Calanus glacialis* which has been in a decade long decline on the southeastern Grand Banks section has increased dramatically on the Flemish Cap section while their abundance has been relatively high on the Bonavista and Seal Island section. This could be a reflect of differential advection of this species by the Labrador Current but further analyses will be required to determine whether this hypothesis is accurate.

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 but some consistency in some trends may be starting to provide new insights into trophic relationships. 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 the abundance of different zooplankton taxa indicates that variations in production do not follow simple relationships. The absence of observations of primary productivity limits our ability to infer the effect of variations in phytoplankton standing stock on secondary productivity. Difficulties in understanding variations in zooplankton abundance are also confounded by the potential for differential effects of fluctuations in ocean temperature on the physiological processes that affect arctic, sub-arctic and temperate taxa. However, the pattern of variation of each trophic level demonstrates a high degree of regional coherence, with northern and southern portions of the NL 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*b*), 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.

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APPENDIX I - TABLES

Table 1. AZMP sampling missions in the NL region in 2014 and 2015.

Group	Location	Mission ID	Date	# Hydro Stations	# Net/Bottle Stations
Ecosystem Trawl Surveys	NE Newfoundland Shelf and Grand Bank	NED2014-445 TEL130-140	Apr 2-Jun 24, 2014	508	9/4
Ecosystem Trawl Surveys	Grand Bank, NE Newfoundland and Labrador Shelves	TEL-2014-134-138, 142-143	Oct 4-Feb 3, 2014	690	8/3
Ecosystem Trawl Surveys	NE Newfoundland Shelf and Grand Bank, NE	NED2015-450-455 NED2015-458-463	Apr 8-Jun 19, 2015	443	7/4
Ecosystem Trawl Surveys	Newfoundland and Labrador Shelves	TEL2015-150-155	Sep 21-Dec 19, 2015	636	8/2
Seasonal Sections	Grand Bank and NE Newfoundland Shelf	TEL2014-129	Apr 11-29, 2014	132	64
Seasonal Sections	Grand Bank, Newfoundland and Labrador Shelves	TEL2014-132	Jul 9-28, 2014	106	72
Seasonal Sections	Grand Bank and NE Newfoundland Shelf	HUD2014-114	Nov 15-Dec 7, 2014	137	69
Seasonal Sections	Grand Bank and NE Newfoundland Shelf	TEL2015-144	Apr 10-27, 2015	143	69
Seasonal Sections	Grand Bank, Newfoundland and Labrador Shelves	TEL2015-148	Jul 9-27, 2015	171	78
Seasonal Sections	Grand Bank and NE Newfoundland and S Labrador Shelves	HUD2015-115	Nov 15-Dec 7, 2015	157	92
Fixed Station	S27	Ships of Opportunity 2014-	Mar-Dec	28	15
Fixed Station	S27	Ships of Opportunity 2015-	Jan-Dec	34	18
-	-	-	**Totals (2014/2015)**	**1601/1584**	**244/278**

Number of net stations refer to dedicated plankton net occupations at S27 during Ecosystem Trawl Surveys.

APPENDIX II - FIGURES

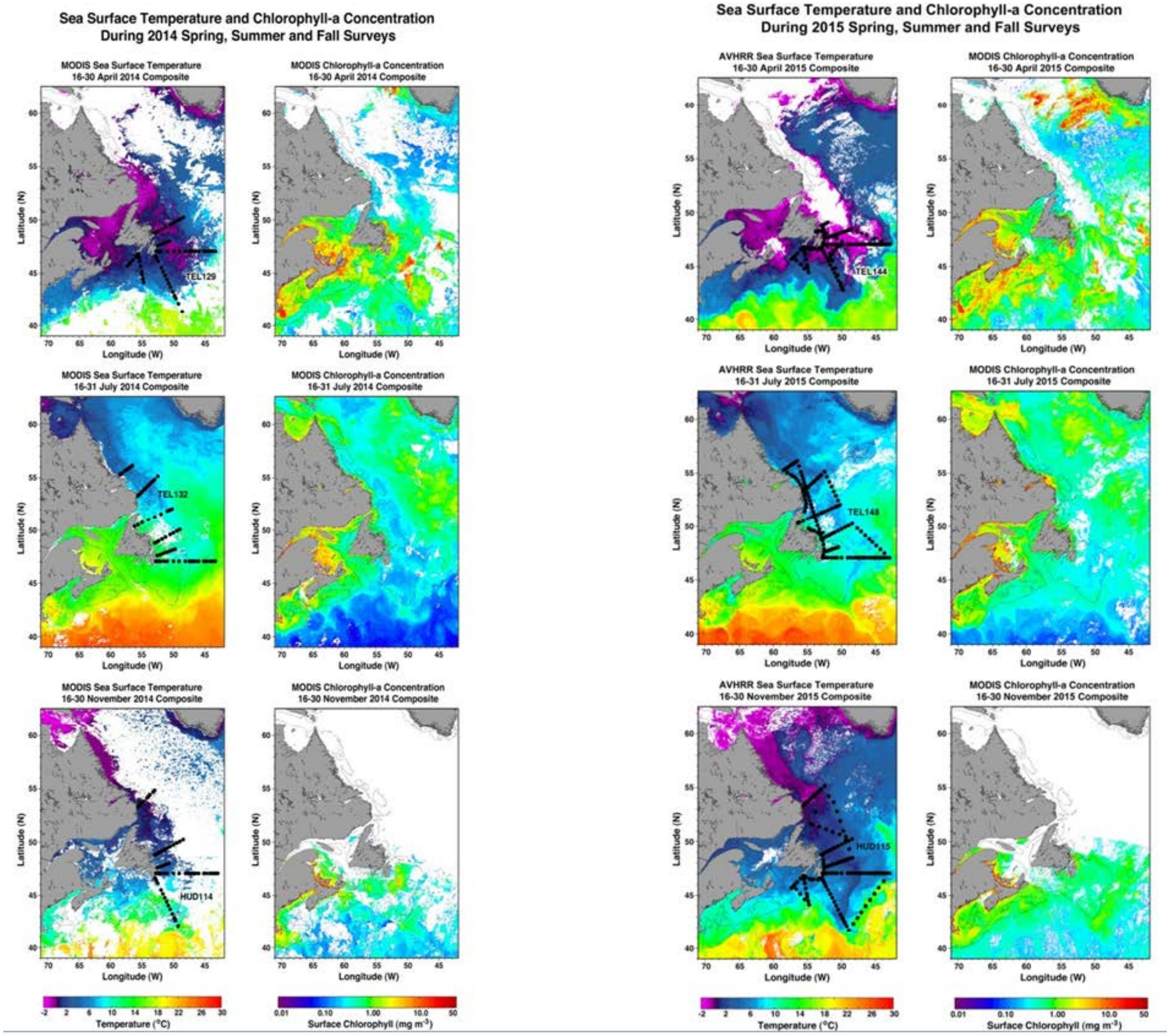


Figure 1. Station occupations during the 2014 (left panels) spring (TEL129), summer (TEL132), and fall (HUD114) section surveys, respectively. Station occupations during the 2015 (right panels) spring (TEL144), summer (TEL148) and fall (HUD115) section surveys, respectively. Station locations superimposed on twice-monthly sea-surface temperature composite images (left-side panels). Corresponding ocean colour composite images provided (right-side panels) for each sampling year and season.

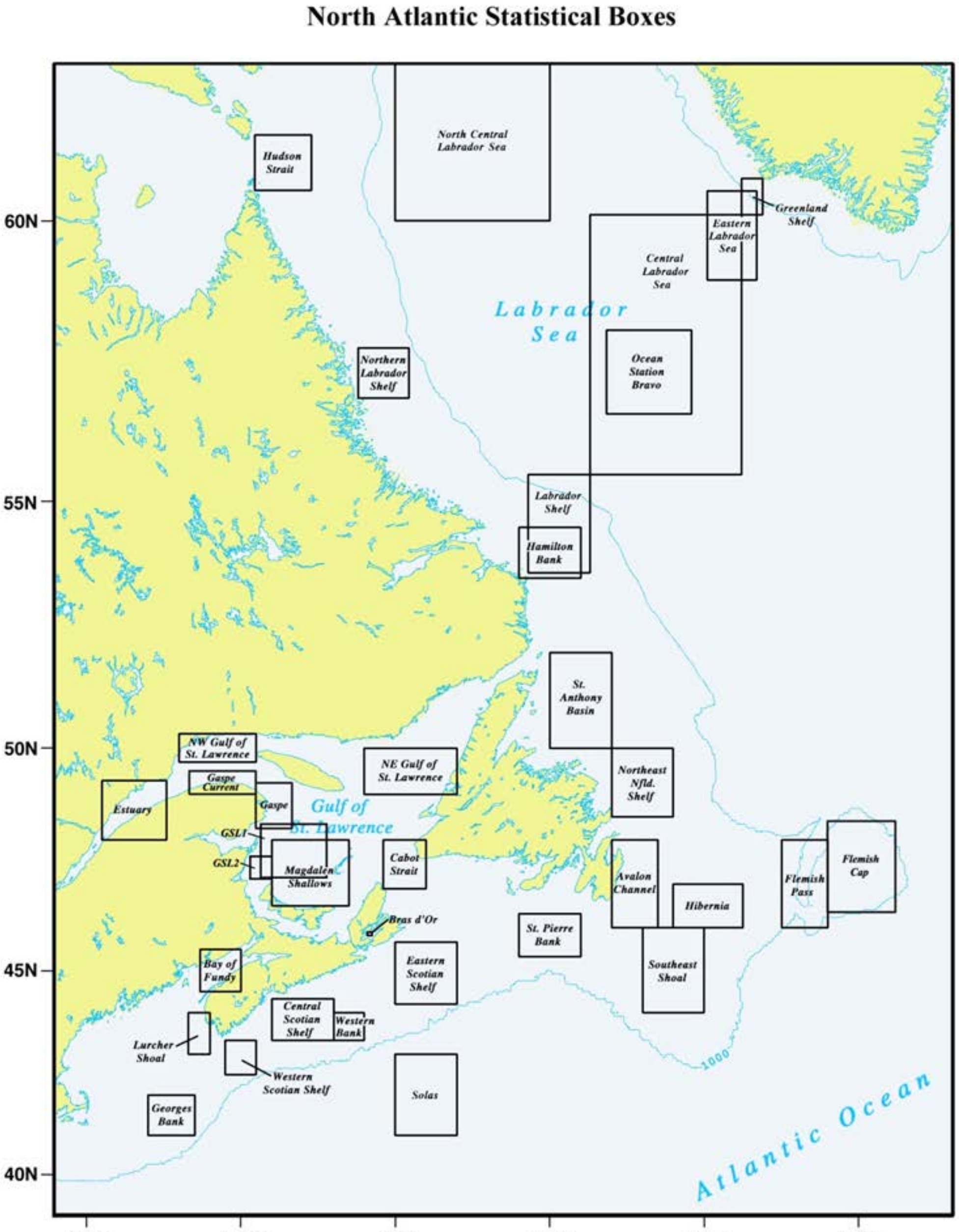


Figure 2. Statistical sub-regions in the Northwest Atlantic identified for spatial/temporal analysis of satellite ocean colour data. Sub-regions in the NL region include St. Pierre Bank (SPB), southeast Shoal (SES), Avalon Channel (AC), Hibernia (HIB), Flemish Pass (FP) and Flemish Cap (FC), northeast Newfoundland Shelf (NENS), St. Anthony Basin (SAB), Hamilton Bank (HB), northern Labrador Shelf (NLS), and Hudson Strait (HS).

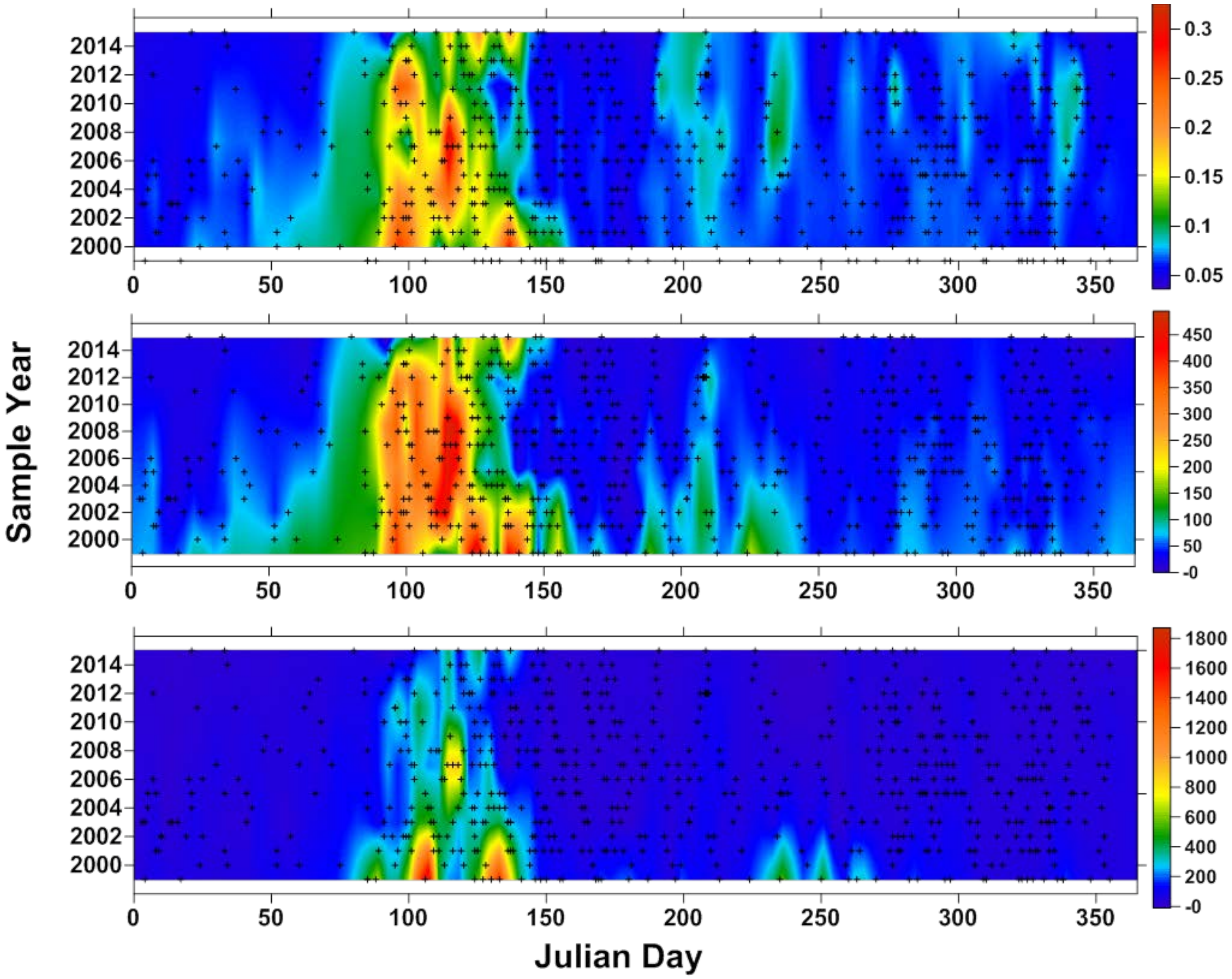


Figure 3. Optical and chlorophyll a pigment properties determined from in-situ PAR (photosynthetic active radiation) and combination of discrete extracted and fluorometric chlorophyll a profiling at S27 during 1999 to 2015. Vertical attenuation coefficient in m^{-1} (top panel; data only from 2000 onward) for the upper 50 m of the water column determined from PAR or model estimate derived from calibrated in-situ chlorophyll a fluorescence, integrated chlorophyll a (mg m^{-2}) within the upper 100 m of the water column based on extracted pigment (middle panel), and integrated calibrated chlorophyll a fluorescence within the upper 100 m of the water column (mg m^{-2}; lower panel). Plus symbols in contour maps indicate timing of respective measurements for different optical and biological indices.

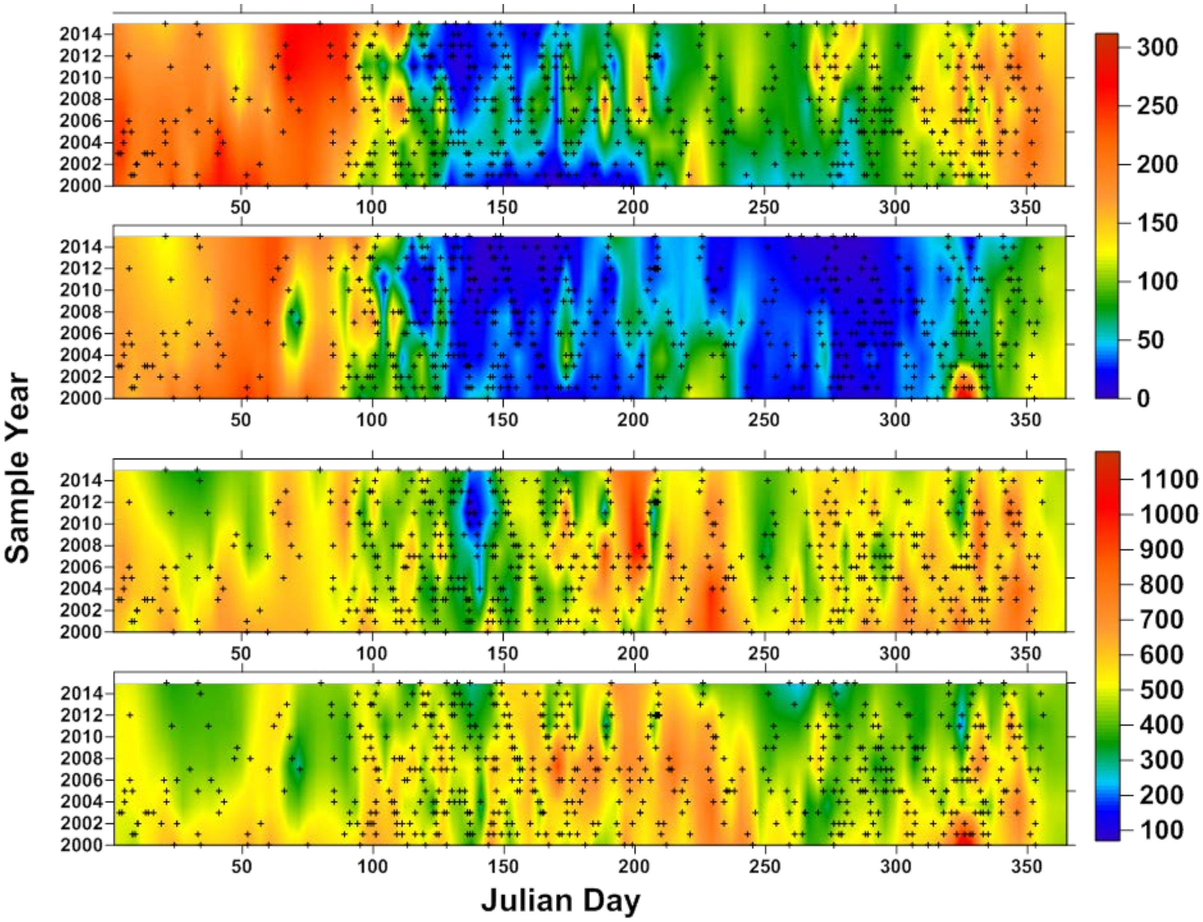


Figure 4. Shallow and deep nutrient inventories at S27 during 2000 to 2015. Shallow (upper 50 m) inventories of silicate and nitrate (mmol m^{-2}; upper two panels respectively) along with corresponding deep (50-150 m) inventories of silicate and nitrate (mmol m^{-2}; lower two panels respectively). Plus symbols in contour maps indicate timing of respective measurements for the nutrient inventories at S27.

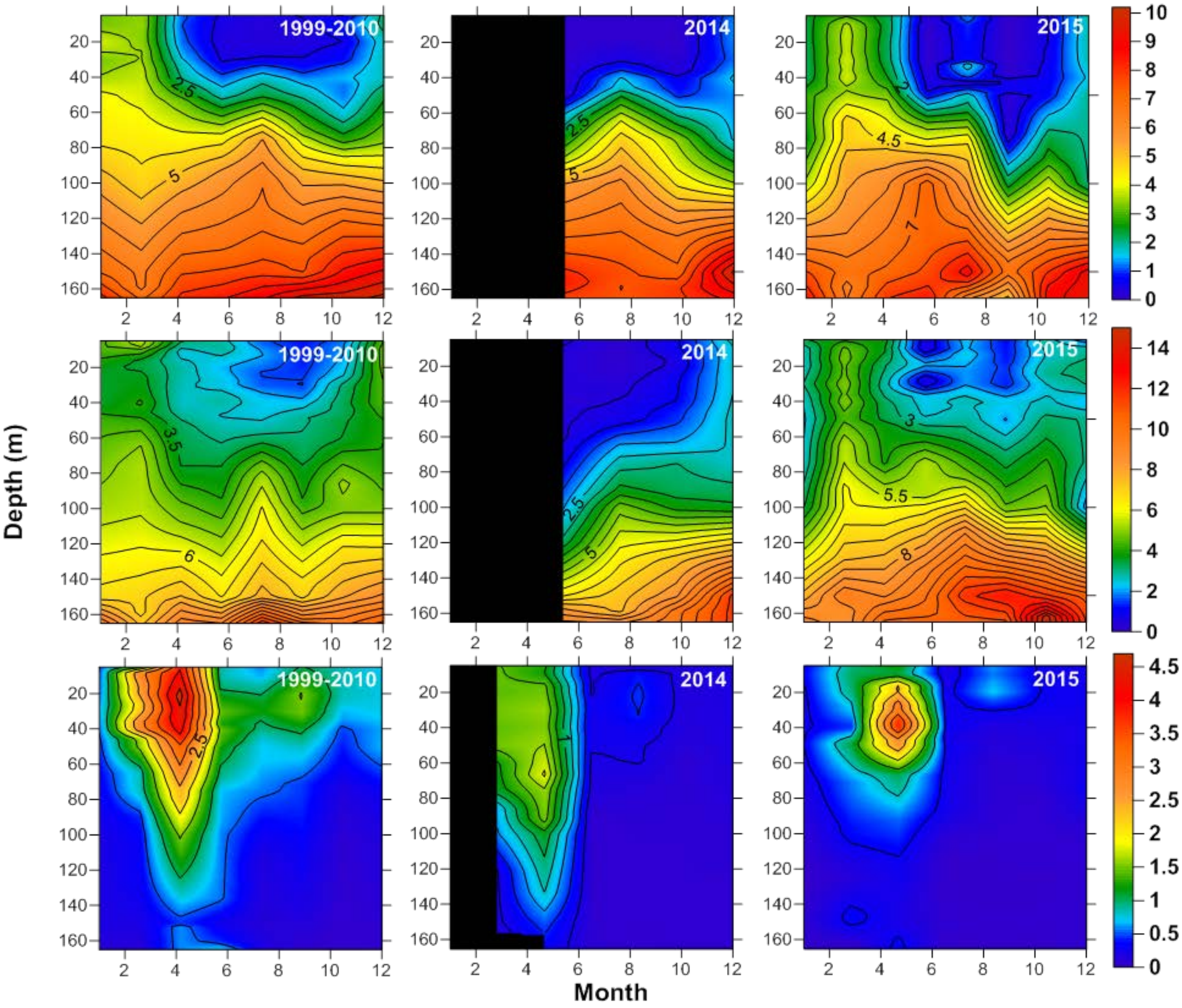


Figure 5. Comparison of vertical structure of nitrate (top panels) and silicate (middle panels) in mmol m^{-3} and chlorophyll concentrations (lower panels) in mg m^{-3} in 2014 and 2015 with mean conditions from 1999-2010 at the NL region fixed coastal station. Gridding method to generate contour plots using triangulation with linear interpolation. Missing monthly observations in 2014 are shown in black.

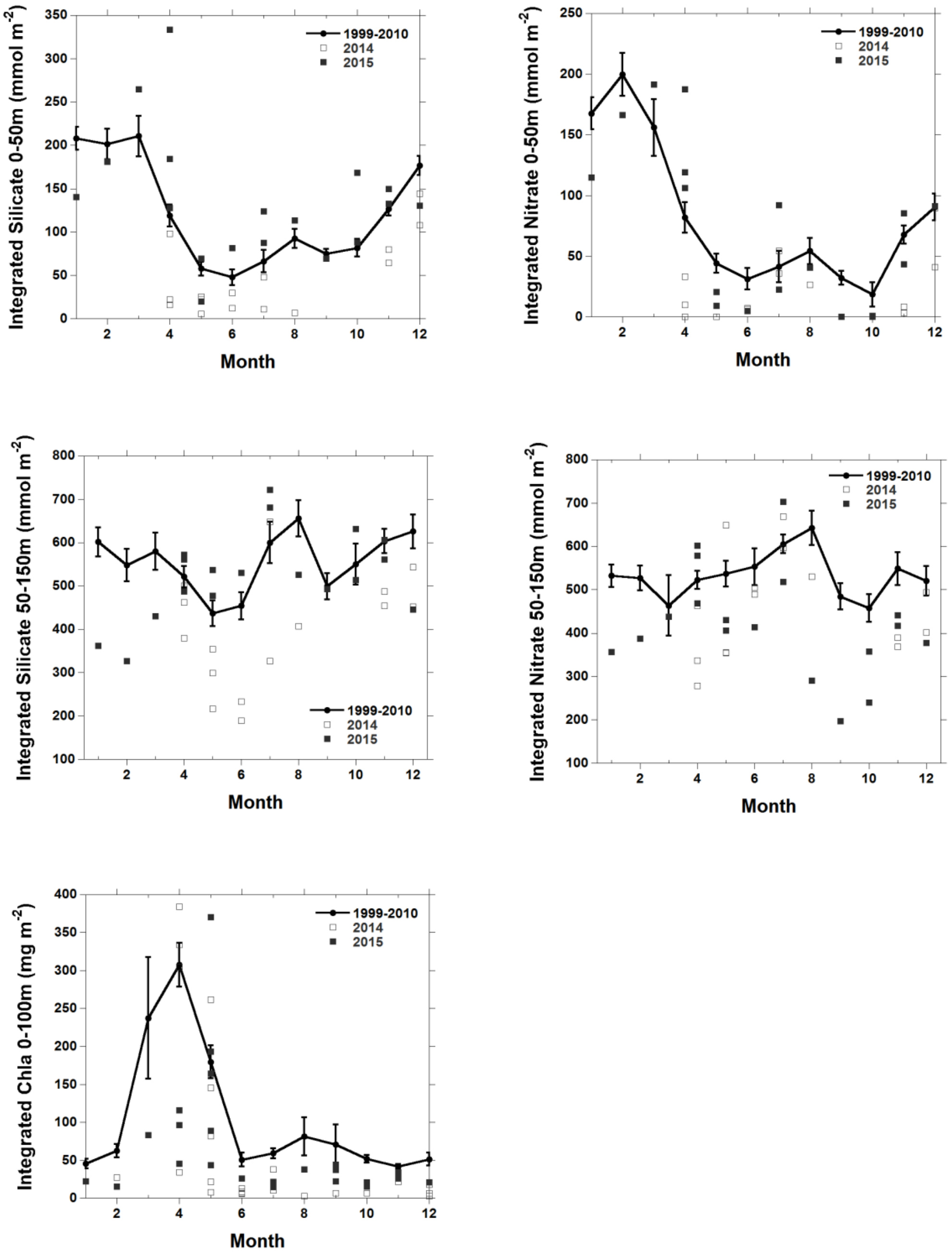


Figure 6. Comparison of annual variability in nutrient inventories (silicate and nitrate) and chlorophyll in 2014 and 2015 with mean conditions from 1999-2010 at the Newfoundland and Labrador Region fixed station (S27). The vertical lines are the standard error of the monthly means.

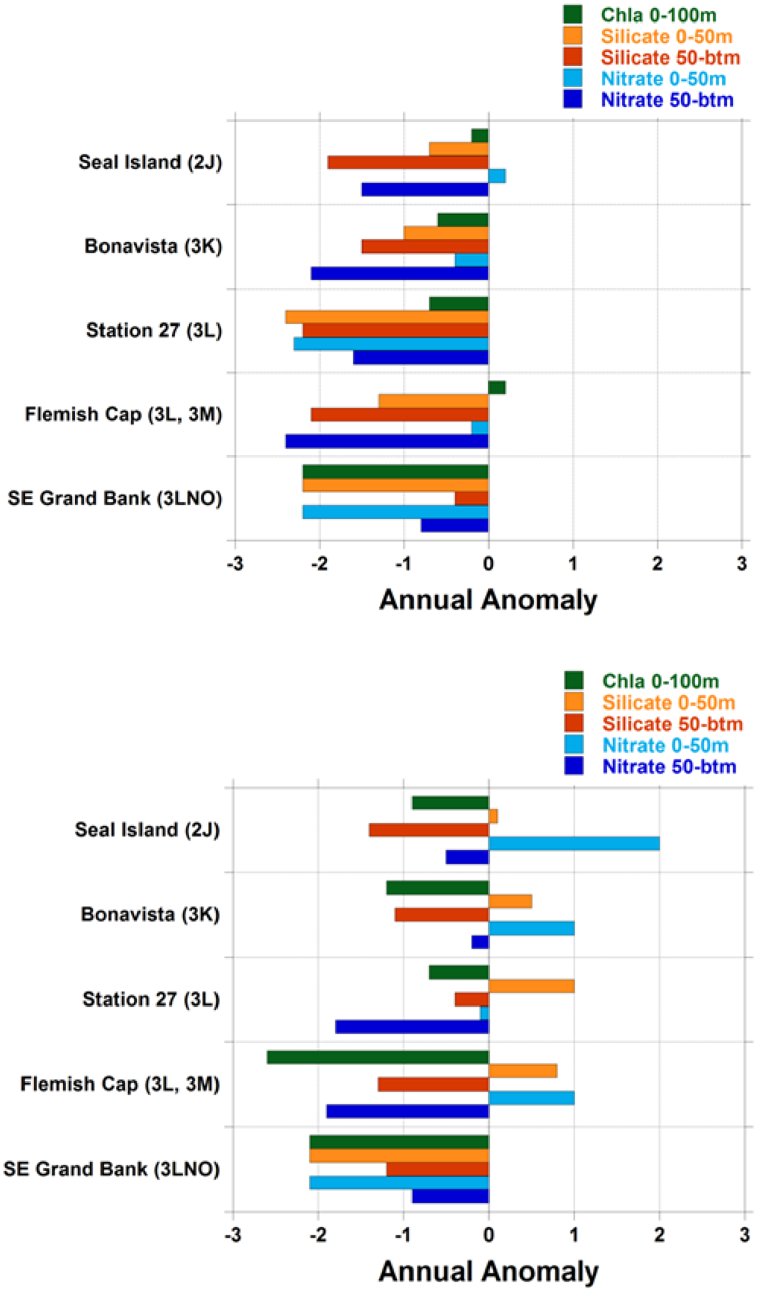
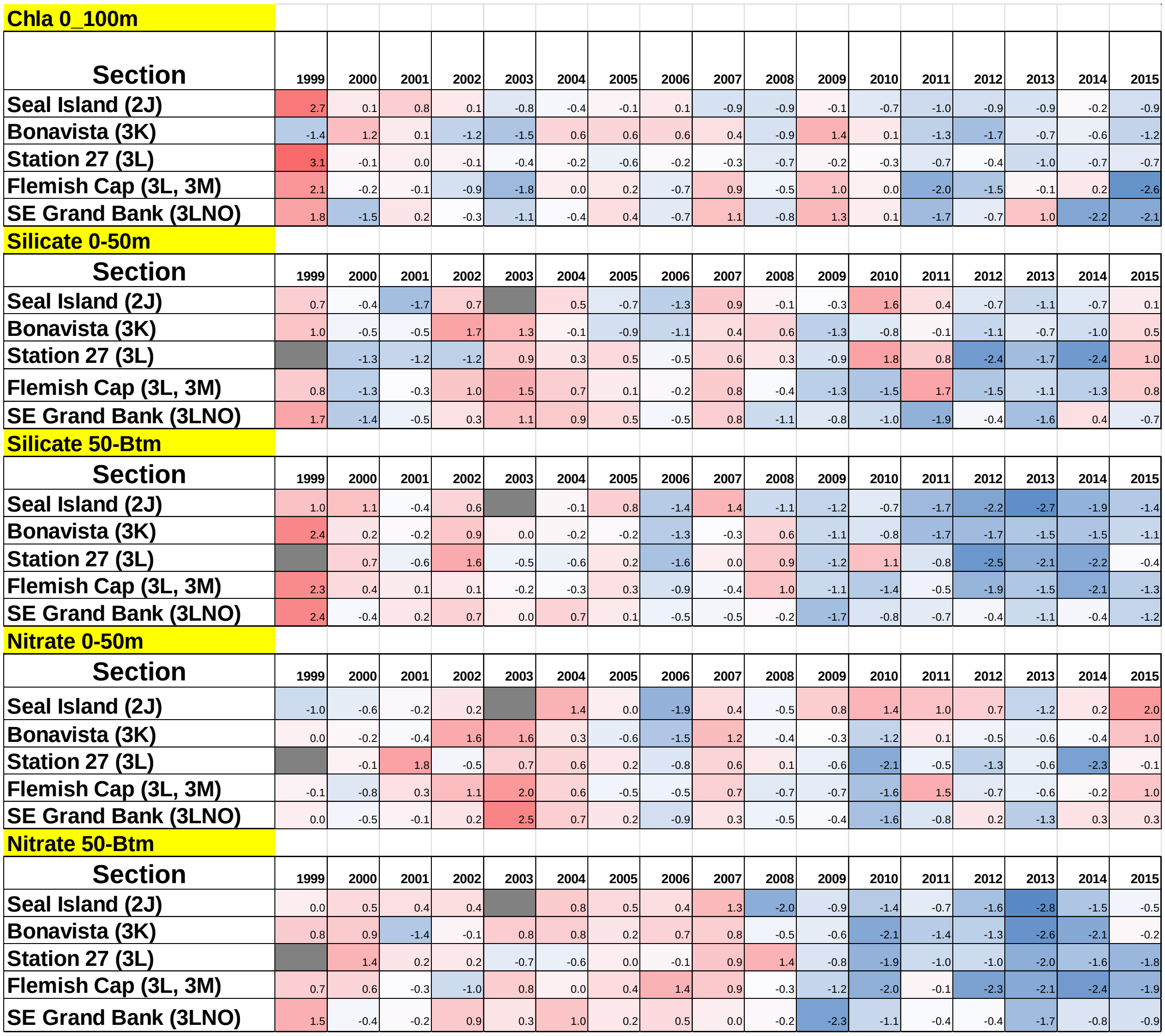


Figure 7. Summary of annual anomalies of chlorophyll and nutrient inventories from the Sections and Fixed Station (S27) during 2014 (top panel) and 2015 (lower panel). The standardized anomalies are the differences between the annual average for 2015 and the long-term mean (1999-2010) divided by the standard deviation. The Sections and fixed station (S27) are sorted from northern (top) to southern (bottom). Negative anomalies imply below average levels while positive values indicate the reverse.



Chla 0_100m

Section	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Seal Island (2J)	2.7	0.1	0.8	0.1	-0.8	-0.4	-0.1	0.1	-0.9	-0.9	-0.1	-0.7	-1.0	-0.9	-0.9	-0.2	-0.9
Bonavista (3K)	-1.4	1.2	0.1	-1.2	-1.5	0.6	0.6	0.6	0.4	-0.9	1.4	0.1	-1.3	-1.7	-0.7	-0.6	-1.2
Station 27 (3L)	3.1	-0.1	0.0	-0.1	-0.4	-0.2	-0.6	-0.2	-0.3	-0.7	-0.2	-0.3	-0.7	-0.4	-1.0	-0.7	-0.7
Flemish Cap (3L, 3M)	2.1	-0.2	-0.1	-0.9	-1.8	0.0	0.2	-0.7	0.9	-0.5	1.0	0.0	-2.0	-1.5	-0.1	0.2	-2.6
SE Grand Bank (3LNO)	1.8	-1.5	0.2	-0.3	-1.1	-0.4	0.4	-0.7	1.1	-0.8	1.3	0.1	-1.7	-0.7	1.0	-2.2	-2.1

Silicate 0-50m

Section	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Seal Island (2J)	0.7	-0.4	-1.7	0.7		0.5	-0.7	-1.3	0.9	-0.1	-0.3	1.6	0.4	-0.7	-1.1	-0.7	0.1
Bonavista (3K)	1.0	-0.5	-0.5	1.7	1.3	-0.1	-0.9	-1.1	0.4	0.6	-1.3	-0.8	-0.1	-1.1	-0.7	-1.0	0.5
Station 27 (3L)		-1.3	-1.2	-1.2	0.9	0.3	0.5	-0.5	0.6	0.3	-0.9	1.8	0.8	-2.4	-1.7	-2.4	1.0
Flemish Cap (3L, 3M)	0.8	-1.3	-0.3	1.0	1.5	0.7	0.1	-0.2	0.8	-0.4	-1.3	-1.5	1.7	-1.5	-1.1	-1.3	0.8
SE Grand Bank (3LNO)	1.7	-1.4	-0.5	0.3	1.1	0.9	0.5	-0.5	0.8	-1.1	-0.8	-1.0	-1.9	-0.4	-1.6	0.4	-0.7

Silicate 50-Btm

Section	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Seal Island (2J)	1.0	1.1	-0.4	0.6		-0.1	0.8	-1.4	1.4	-1.1	-1.2	-0.7	-1.7	-2.2	-2.7	-1.9	-1.4
Bonavista (3K)	2.4	0.2	-0.2	0.9	0.0	-0.2	-0.2	-1.3	-0.3	0.6	-1.1	-0.8	-1.7	-1.7	-1.5	-1.5	-1.1
Station 27 (3L)		0.7	-0.6	1.6	-0.5	-0.6	0.2	-1.6	0.0	0.9	-1.2	1.1	-0.8	-2.5	-2.1	-2.2	-0.4
Flemish Cap (3L, 3M)	2.3	0.4	0.1	0.1	-0.2	-0.3	0.3	-0.9	-0.4	1.0	-1.1	-1.4	-0.5	-1.9	-1.5	-2.1	-1.3
SE Grand Bank (3LNO)	2.4	-0.4	0.2	0.7	0.0	0.7	0.1	-0.5	-0.5	-0.2	-1.7	-0.8	-0.7	-0.4	-1.1	-0.4	-1.2

Nitrate 0-50m

Section	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Seal Island (2J)	-1.0	-0.6	-0.2	0.2		1.4	0.0	-1.9	0.4	-0.5	0.8	1.4	1.0	0.7	-1.2	0.2	2.0
Bonavista (3K)	0.0	-0.2	-0.4	1.6	1.6	0.3	-0.6	-1.5	1.2	-0.4	-0.3	-1.2	0.1	-0.5	-0.6	-0.4	1.0
Station 27 (3L)		-0.1	1.8	-0.5	0.7	0.6	0.2	-0.8	0.6	0.1	-0.6	-2.1	-0.5	-1.3	-0.6	-2.3	-0.1
Flemish Cap (3L, 3M)	-0.1	-0.8	0.3	1.1	2.0	0.6	-0.5	-0.5	0.7	-0.7	-0.7	-1.6	1.5	-0.7	-0.6	-0.2	1.0
SE Grand Bank (3LNO)	0.0	-0.5	-0.1	0.2	2.5	0.7	0.2	-0.9	0.3	-0.5	-0.4	-1.6	-0.8	0.2	-1.3	0.3	0.3

Nitrate 50-Btm

Section	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Seal Island (2J)	0.0	0.5	0.4	0.4		0.8	0.5	0.4	1.3	-2.0	-0.9	-1.4	-0.7	-1.6	-2.8	-1.5	-0.5
Bonavista (3K)	0.8	0.9	-1.4	-0.1	0.8	0.8	0.2	0.7	0.8	-0.5	-0.6	-2.1	-1.4	-1.3	-2.6	-2.1	-0.2
Station 27 (3L)		1.4	0.2	0.2	-0.7	-0.6	0.0	-0.1	0.9	1.4	-0.8	-1.9	-1.0	-1.0	-2.0	-1.6	-1.8
Flemish Cap (3L, 3M)	0.7	0.6	-0.3	-1.0	0.8	0.0	0.4	1.4	0.9	-0.3	-1.2	-2.0	-0.1	-2.3	-2.1	-2.4	-1.9
SE Grand Bank (3LNO)	1.5	-0.4	-0.2	0.9	0.3	1.0	0.2	0.5	0.0	-0.2	-2.3	-1.1	-0.4	-0.4	-1.7	-0.8	-0.9

Figure 8. Annual scorecard anomalies of integrated chlorophyll a (0-100 m; mg m^{-2}) and shallow (0-50 m) and deep (50 m-bottom) nutrient (silicate and nitrate; mmol m^{-2}) inventories across the different ocean sections and fixed station (S27). The numbers in the boxes are normalized anomalies. Nutrient data was not available for the Fixed Station in 1999 and Seal Island Section in 2003.

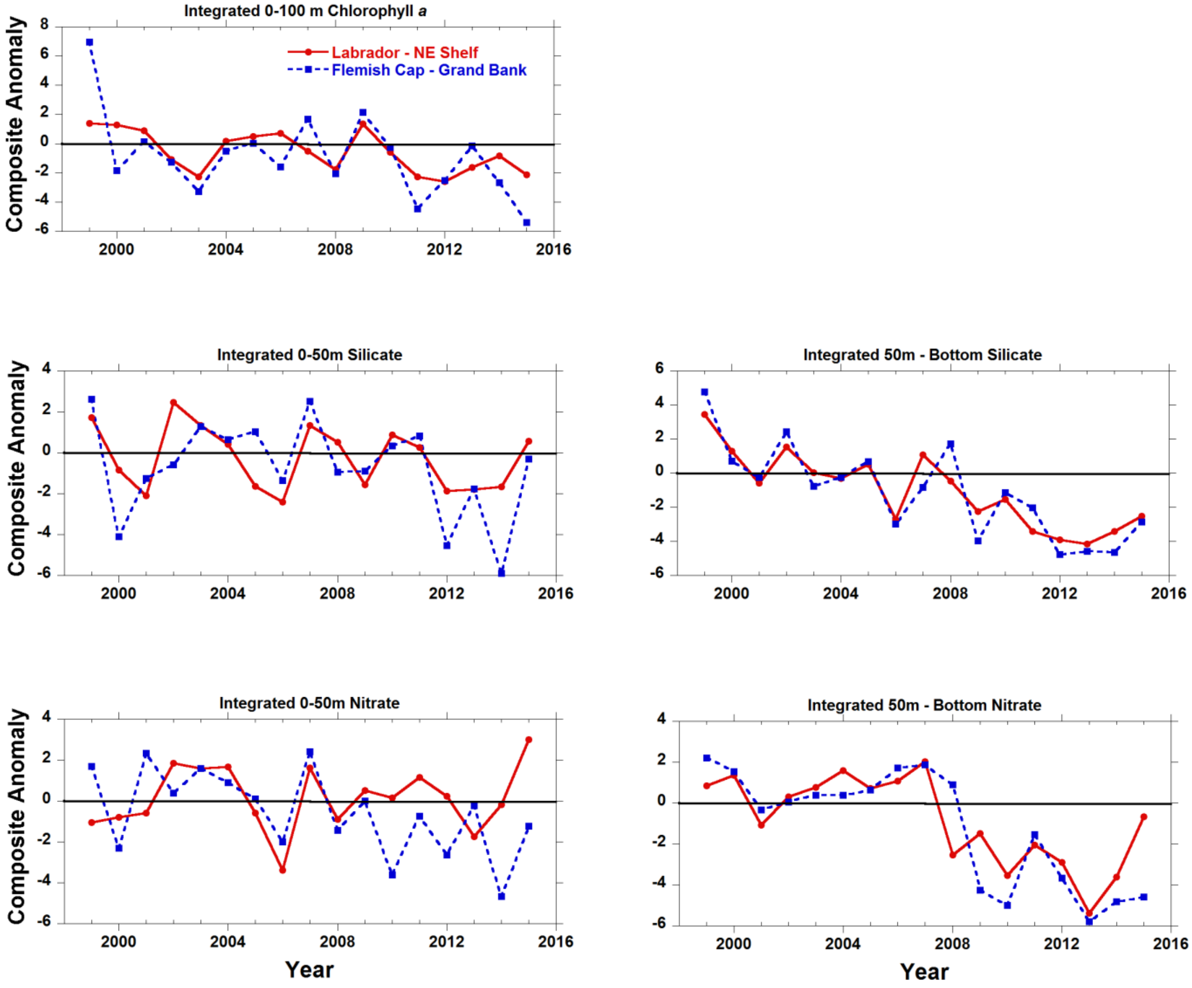


Figure 9. Composite (summed) annual anomalies of chlorophyll a and nutrient inventories across the Labrador and northeast Newfoundland Shelf and Grand Bank – Flemish Cap Sections and fixed station (S27) during 1998 to 2015. The upper panel show the water-column integrated chlorophyll a inventories; middle panels show the shallow and deep silicate inventories; bottom panels show the corresponding nitrate inventories; bottom left panel shows. The summed standardized anomalies are the differences between the annual average for a given year and the long-term mean (1999-2010) divided by the standard deviation. Negative anomalies imply below average levels while positive values indicate the reverse.

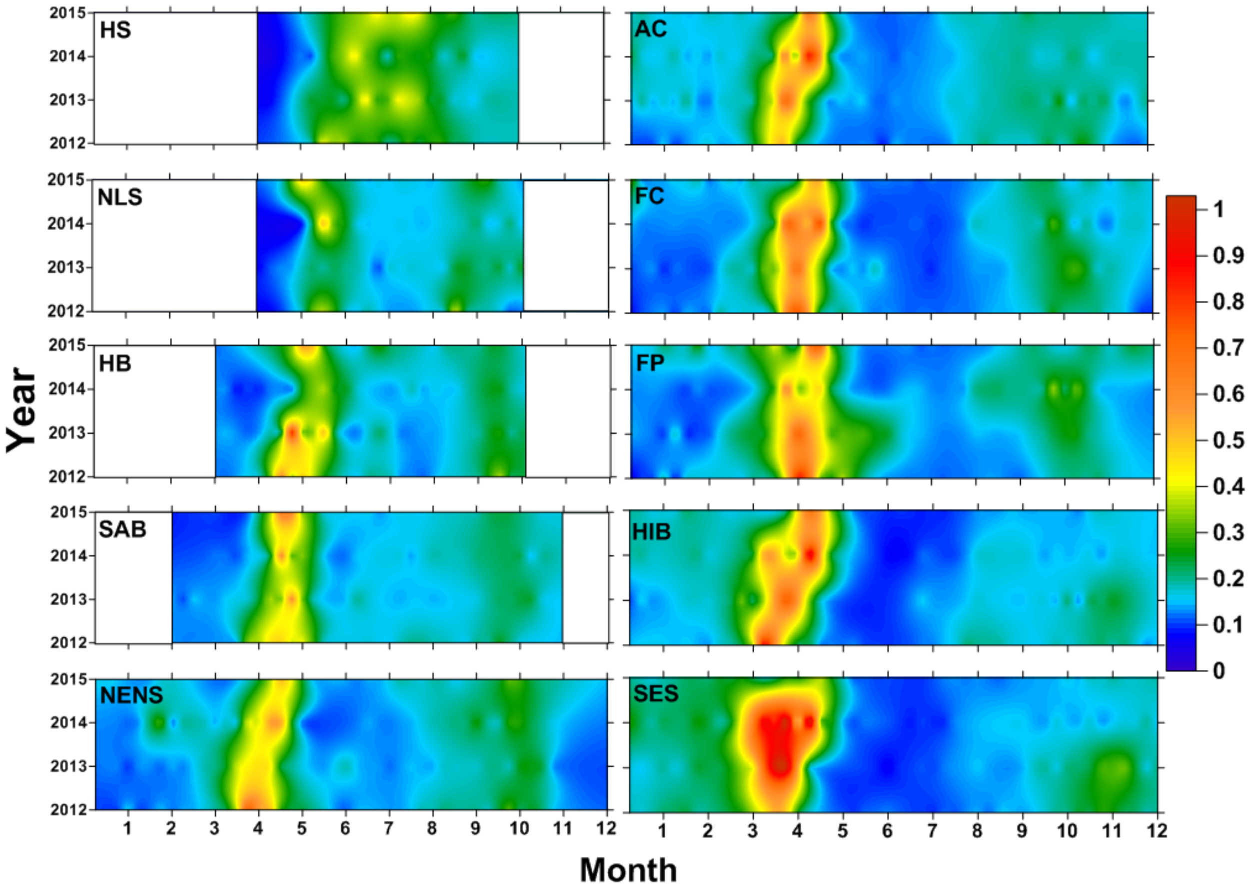


Figure 10. Time-series of surface chlorophyll a concentrations (log-transformed + 1; mg m^{-3}), from VIIRS ocean colour data along statistical sub-regions across the Newfoundland and Labrador area during 2012-15. See Figure 2 for locations of statistical sub-regions in the NL area. Normal ice-covered periods are blocked out in white. See Figure 2 for actual locations of statistical sub-regions.

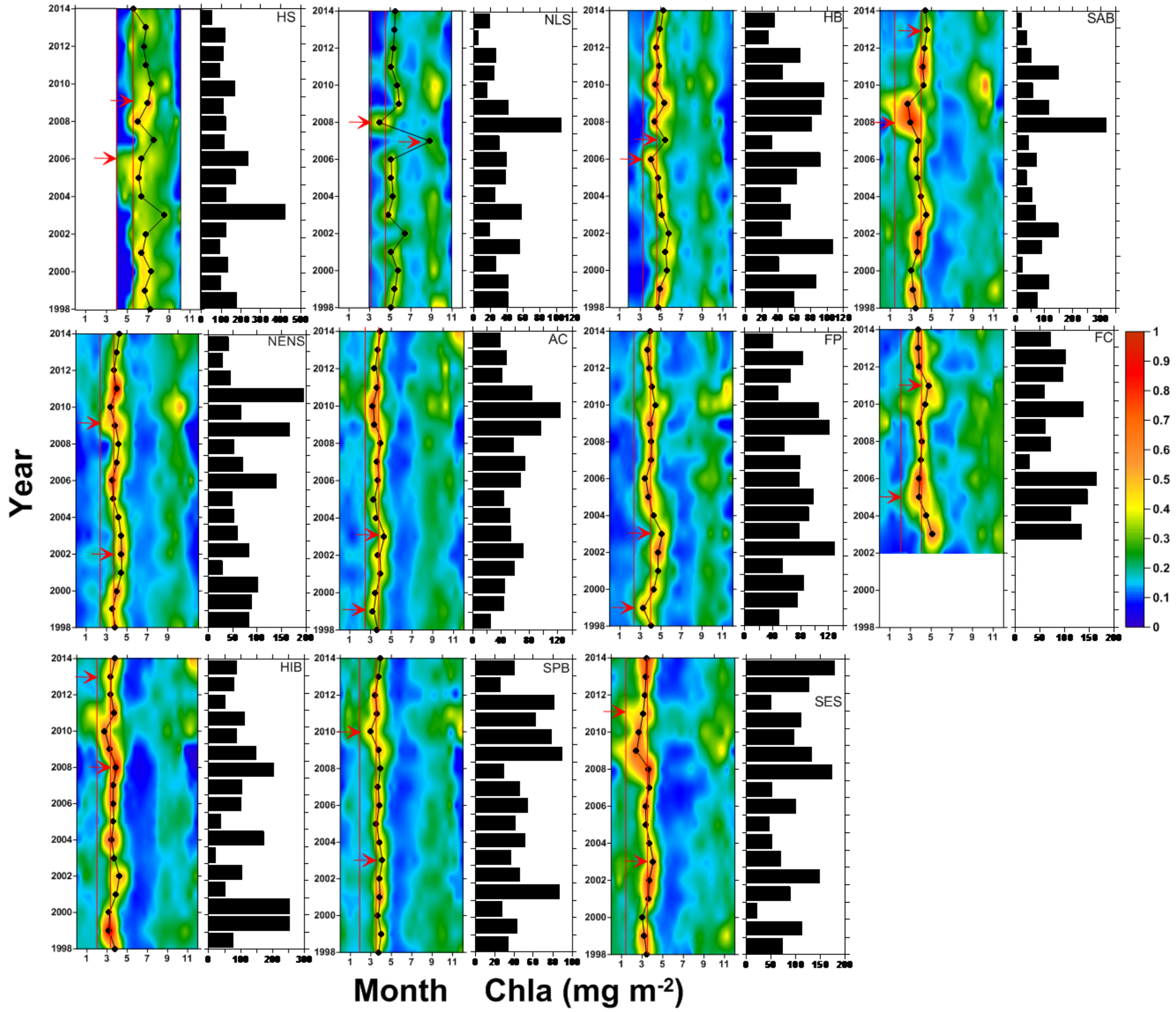
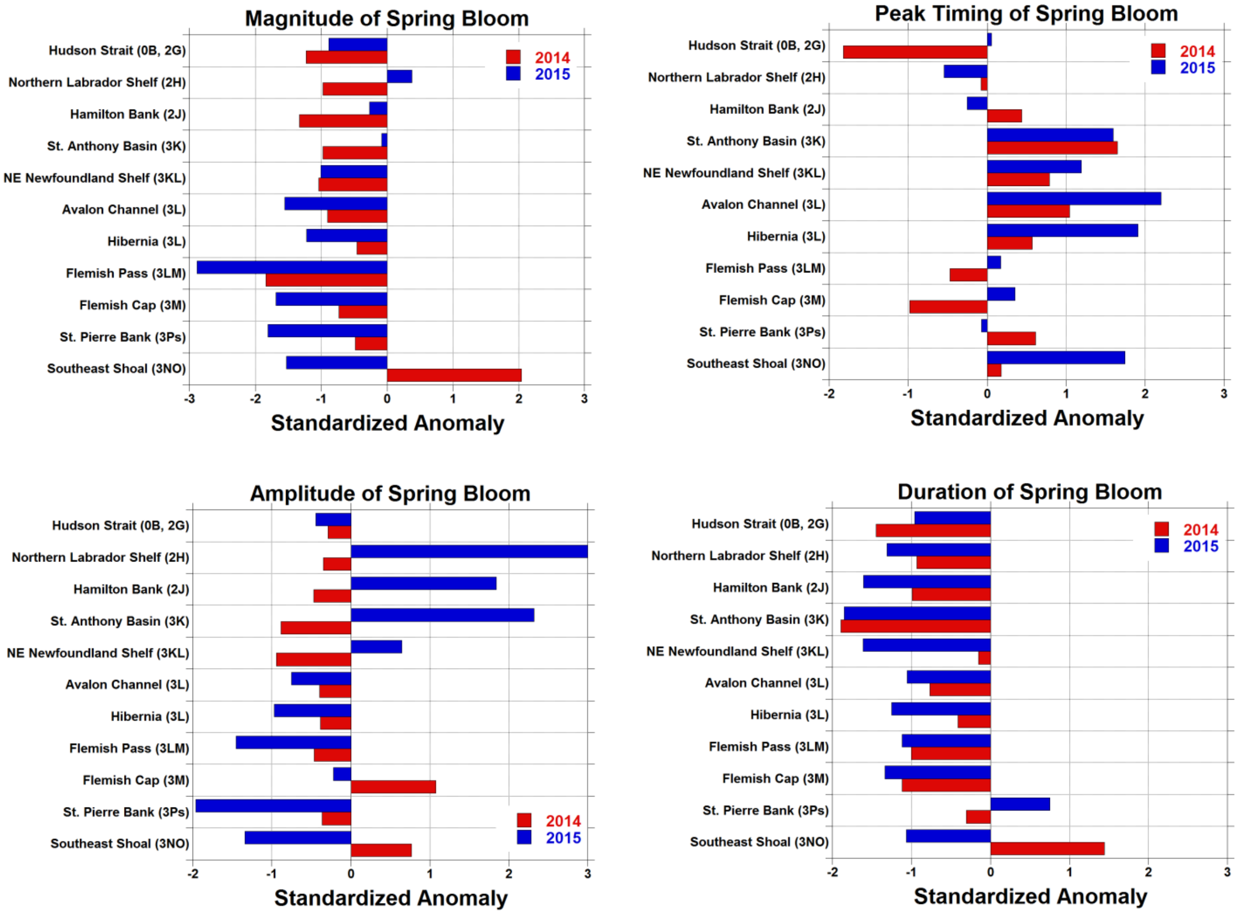


Figure 11. Time-series of surface chlorophyll a concentrations (log-transformed + 1; mg m^{-3}), from combined SeaWiFS and MODIS ocean colour data along statistical sub-regions across the Newfoundland and Labrador area during 1998-2014 (not including the 2015 VIIRS data). SeaWifs data for the Flemish Cap was not available prior to July 2002. See Figure 2 for locations of statistical sub-regions in Newfoundland and Labrador area. Normal ice-covered periods and unavailable data are blocked out in white. Corresponding bar charts (right panels) is the integral of chlorophyll a (Chla mg m^{-2}) concentration under the Gaussian curve (see methods). Time series of peak timing of the spring bloom shown (solid black line) and the earliest and latest initiation of the spring bloom (solid red lines) and respective years (red arrows).



Magnitude of Spring Bloom

Peak Timing of Spring Bloom

Amplitude of Spring Bloom

Duration of Spring Bloom

Figure 12. Summary of annual ocean colour anomalies from Moderate Resolution Imaging Spectroradiometer (MODIS) “Aqua” sensor imagery across the different statistical sub-regions during 2014 and 2015. The left panels show the biomass metrics of the spring production cycle while the right panels indicate the different timing indices derived from the shifted Gaussian model (see methods for description). The standardized anomalies are the differences between the annual average for a given year and the long-term mean (1998-2010) divided by the standard deviation. The statistical sub-regions are sorted from northern (top) to southern (bottom) boxes. Negative anomalies for the timing indices indicate earlier/shorter blooms while positive anomalies indicate the reverse.

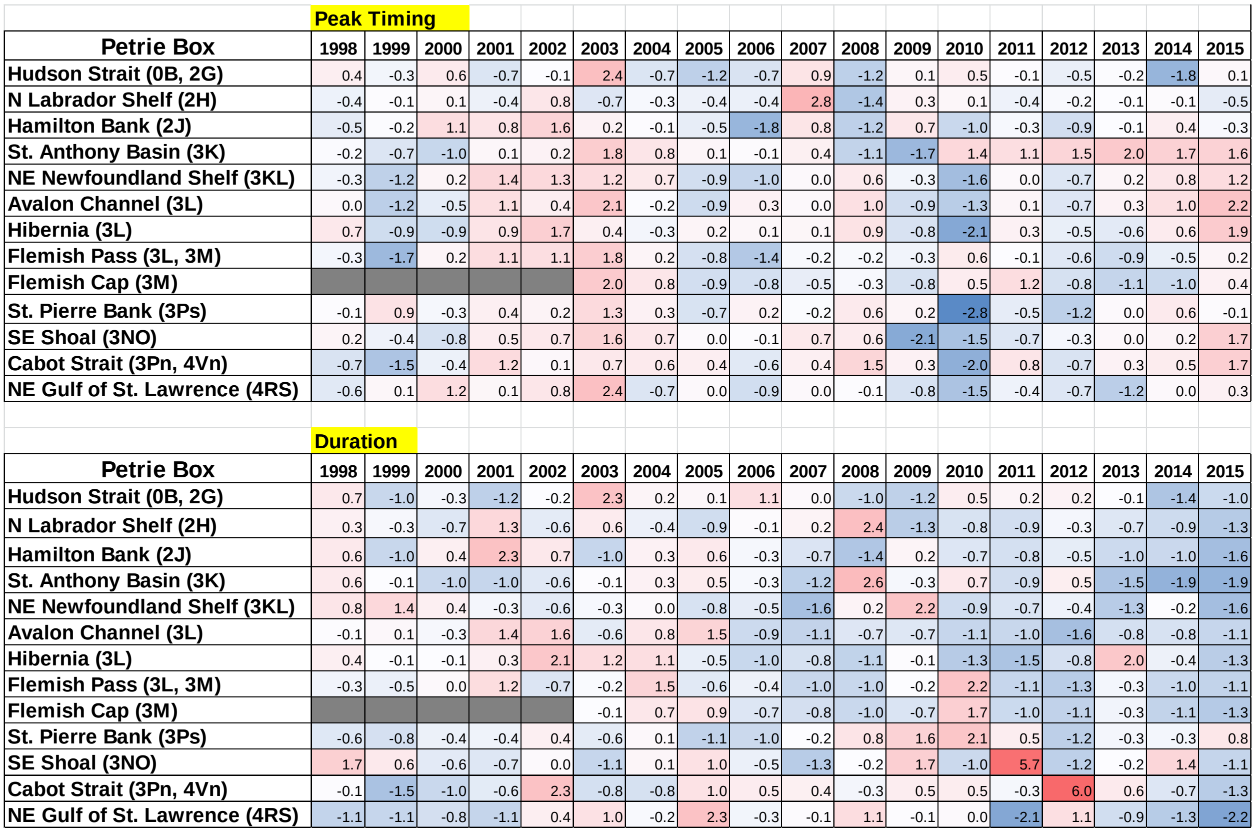
Magnitude

Petrie Box	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Hudson Strait (0B, 2G)	0.2	-0.7	-0.3	-0.8	-0.5	3.0	-0.4	0.1	0.8	-0.5	-0.4	-0.6	0.1	-0.8	-0.6	-0.5	-1.2	-0.9
N Labrador Shelf (2H)	0.0	0.0	-0.7	0.6	-1.0	0.7	-0.7	-0.1	-0.1	-0.5	2.8	0.0	-1.1	-0.8	-0.7	-1.6	-1.0	0.4
Hamilton Bank (2J)	-0.4	0.7	-1.1	1.5	-1.0	-0.5	-1.0	-0.2	0.9	-1.5	0.5	1.0	1.1	-0.9	-0.1	-1.6	-1.3	-0.3
St. Anthony Basin (3K)	-0.3	0.3	-0.9	0.0	0.7	-0.3	-0.5	-0.8	-0.3	-0.6	3.0	0.3	-0.5	0.7	-0.5	-0.7	-1.0	-0.1
NE Newfoundland Shelf (3KL)	0.1	0.2	0.6	-1.4	0.1	-0.5	-0.7	-0.8	1.6	-0.2	-0.7	2.3	-0.4	3.1	-0.9	-1.3	-1.0	-1.0
Avalon Channel (3L)	-1.5	-0.7	-0.7	-0.2	0.4	-0.3	-0.4	-0.8	0.2	0.4	-0.2	1.3	2.4	0.8	-0.9	-0.6	-0.9	-1.6
Hibernia (3L)	-0.6	1.7	1.7	-0.9	-0.2	-1.3	0.6	-1.1	-0.3	-0.3	1.0	0.3	-0.5	-0.1	-1.0	-0.6	-0.5	-1.2
Flemish Pass (3L, 3M)	-1.5	-0.4	0.0	-1.2	1.8	-0.3	0.3	0.6	-0.3	-0.2	-1.1	1.5	0.9	-1.5	-0.8	-0.1	-1.8	-2.9
Flemish Cap (3M)						0.6	0.1	0.8	1.2	-1.6	-0.7	-1.0	0.6	-1.0	-0.2	-0.1	-0.7	-1.7
St. Pierre Bank (3Ps)	-0.8	-0.4	-1.1	1.7	-0.2	-0.7	0.0	-0.5	0.1	-0.2	-1.0	1.8	1.3	0.5	1.4	-1.2	-0.5	-1.8
SE Shoal (3NO)	-0.4	0.5	-1.6	0.0	1.3	-0.5	-0.8	-1.0	0.2	-0.8	1.9	1.0	0.2	0.5	-0.9	0.8	2.0	-1.5
Cabot Strait (3Pn, 4Vn)	1.1	0.3	0.0	-0.8	0.2	0.3	-0.6	-1.2	2.1	1.0	-1.3	-0.1	-1.0	0.1	1.6	-0.3	0.1	-1.2
NE Gulf of St. Lawrence (4RS)	1.7	-1.0	-1.2	-0.1	-0.7	-0.3	0.4	-0.6	-0.2	0.3	-0.5	-0.1	2.3	-0.2	-0.3	0.9	-1.8	-2.3

Amplitude

Petrie Box	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Hudson Strait (0B, 2G)	-0.7	0.4	-0.4	0.8	-0.9	1.0	-1.3	-0.1	-0.2	-1.3	1.4	1.7	-0.7	-2.0	-1.7	-1.0	-0.3	-0.4
N Labrador Shelf (2H)	-0.4	0.1	-0.2	-0.5	-0.8	0.0	-0.5	1.0	-0.2	-0.7	0.1	2.9	-0.7	-0.1	-0.6	-1.5	-0.3	4.4
Hamilton Bank (2J)	-0.7	1.3	-1.0	-0.5	-0.9	0.3	-0.9	-0.6	0.5	-0.7	2.1	0.1	1.0	-0.3	0.1	-0.7	-0.5	1.8
St. Anthony Basin (3K)	-0.5	0.5	-1.1	0.8	1.8	-0.4	-0.8	-1.2	-0.2	-0.4	1.6	0.6	-0.8	2.2	-0.8	-0.5	-0.9	2.3
NE Newfoundland Shelf (3KL)	-0.5	-0.7	0.0	-1.2	0.4	-0.5	-0.7	-0.4	1.9	2.1	-0.8	0.0	0.3	4.0	-0.7	-0.6	-0.9	0.6
Avalon Channel (3L)	-1.0	-0.6	-0.5	-0.7	-0.6	-0.1	-0.6	-0.9	0.6	0.9	0.0	1.0	2.5	1.1	0.4	-0.1	-0.4	-0.7
Hibernia (3L)	-0.7	1.4	1.4	-1.0	-0.8	-1.3	-0.1	-1.0	0.1	0.0	1.8	0.2	0.0	0.7	-0.8	-0.9	-0.4	-1.0
Flemish Pass (3L, 3M)	-0.9	-0.1	-0.4	-1.4	2.0	-0.3	-1.0	0.9	0.0	1.2	0.3	0.7	-1.0	0.0	1.6	-0.1	-0.5	-1.5
Flemish Cap (3M)						0.4	-0.6	-0.4	2.1	-1.0	0.6	-0.3	-0.8	0.1	2.1	0.1	1.1	-0.2
St. Pierre Bank (3Ps)	-0.4	0.4	-1.0	2.1	-0.7	-0.3	-0.3	1.0	1.5	-0.2	-1.4	-0.1	-0.6	-0.1	4.7	-1.1	-0.4	-2.0
SE Shoal (3NO)	-0.9	0.1	-1.5	0.3	1.2	0.1	-0.9	-1.3	0.5	-0.3	1.9	-0.1	0.9	-1.1	-0.4	0.8	0.8	-1.3
Cabot Strait (3Pn, 4Vn)	1.1	1.0	0.3	-0.7	-0.4	0.6	-0.4	-1.3	1.7	0.8	-1.3	-0.3	-1.1	0.1	-0.2	-0.5	0.3	-1.1
NE Gulf of St. Lawrence (4RS)	2.4	-0.3	-0.6	0.6	-0.8	-0.7	0.3	-1.2	-0.1	0.1	-0.9	-0.2	1.4	2.7	-0.8	1.3	-1.0	-1.2

Figure 13. Annual standardized scorecard anomaly indices for magnitude (integrated chlorophyll a concentration), and amplitude (intensity) of the spring bloom across the Newfoundland and Labrador statistical sub-regions during 1998-2015. The standardized anomalies are the differences between the annual average for a given year and the long-term mean (1998-2010) divided by the standard deviation. The numbers in the boxes are normalized anomalies. The statistical sub-regions are sorted from northern (top) to southern (bottom) boxes. Blank grey cells indicate the fitting routine could not be achieved or data not available. Data for Flemish Cap are not available during 1998-2002.



Peak Timing

Petrie Box	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Hudson Strait (0B, 2G)	0.4	-0.3	0.6	-0.7	-0.1	2.4	-0.7	-1.2	-0.7	0.9	-1.2	0.1	0.5	-0.1	-0.5	-0.2	-1.8	0.1
N Labrador Shelf (2H)	-0.4	-0.1	0.1	-0.4	0.8	-0.7	-0.3	-0.4	-0.4	2.8	-1.4	0.3	0.1	-0.4	-0.2	-0.1	-0.1	-0.5
Hamilton Bank (2J)	-0.5	-0.2	1.1	0.8	1.6	0.2	-0.1	-0.5	-1.8	0.8	-1.2	0.7	-1.0	-0.3	-0.9	-0.1	0.4	-0.3
St. Anthony Basin (3K)	-0.2	-0.7	-1.0	0.1	0.2	1.8	0.8	0.1	-0.1	0.4	-1.1	-1.7	1.4	1.1	1.5	2.0	1.7	1.6
NE Newfoundland Shelf (3KL)	-0.3	-1.2	0.2	1.4	1.3	1.2	0.7	-0.9	-1.0	0.0	0.6	-0.3	-1.6	0.0	-0.7	0.2	0.8	1.2
Avalon Channel (3L)	0.0	-1.2	-0.5	1.1	0.4	2.1	-0.2	-0.9	0.3	0.0	1.0	-0.9	-1.3	0.1	-0.7	0.3	1.0	2.2
Hibernia (3L)	0.7	-0.9	-0.9	0.9	1.7	0.4	-0.3	0.2	0.1	0.1	0.9	-0.8	-2.1	0.3	-0.5	-0.6	0.6	1.9
Flemish Pass (3L, 3M)	-0.3	-1.7	0.2	1.1	1.1	1.8	0.2	-0.8	-1.4	-0.2	-0.2	-0.3	0.6	-0.1	-0.6	-0.9	-0.5	0.2
Flemish Cap (3M)						2.0	0.8	-0.9	-0.8	-0.5	-0.3	-0.8	0.5	1.2	-0.8	-1.1	-1.0	0.4
St. Pierre Bank (3Ps)	-0.1	0.9	-0.3	0.4	0.2	1.3	0.3	-0.7	0.2	-0.2	0.6	0.2	-2.8	-0.5	-1.2	0.0	0.6	-0.1
SE Shoal (3NO)	0.2	-0.4	-0.8	0.5	0.7	1.6	0.7	0.0	-0.1	0.7	0.6	-2.1	-1.5	-0.7	-0.3	0.0	0.2	1.7
Cabot Strait (3Pn, 4Vn)	-0.7	-1.5	-0.4	1.2	0.1	0.7	0.6	0.4	-0.6	0.4	1.5	0.3	-2.0	0.8	-0.7	0.3	0.5	1.7
NE Gulf of St. Lawrence (4RS)	-0.6	0.1	1.2	0.1	0.8	2.4	-0.7	0.0	-0.9	0.0	-0.1	-0.8	-1.5	-0.4	-0.7	-1.2	0.0	0.3

Duration

Petrie Box	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Hudson Strait (0B, 2G)	0.7	-1.0	-0.3	-1.2	-0.2	2.3	0.2	0.1	1.1	0.0	-1.0	-1.2	0.5	0.2	0.2	-0.1	-1.4	-1.0
N Labrador Shelf (2H)	0.3	-0.3	-0.7	1.3	-0.6	0.6	-0.4	-0.9	-0.1	0.2	2.4	-1.3	-0.8	-0.9	-0.3	-0.7	-0.9	-1.3
Hamilton Bank (2J)	0.6	-1.0	0.4	2.3	0.7	-1.0	0.3	0.6	-0.3	-0.7	-1.4	0.2	-0.7	-0.8	-0.5	-1.0	-1.0	-1.6
St. Anthony Basin (3K)	0.6	-0.1	-1.0	-1.0	-0.6	-0.1	0.3	0.5	-0.3	-1.2	2.6	-0.3	0.7	-0.9	0.5	-1.5	-1.9	-1.9
NE Newfoundland Shelf (3KL)	0.8	1.4	0.4	-0.3	-0.6	-0.3	0.0	-0.8	-0.5	-1.6	0.2	2.2	-0.9	-0.7	-0.4	-1.3	-0.2	-1.6
Avalon Channel (3L)	-0.1	0.1	-0.3	1.4	1.6	-0.6	0.8	1.5	-0.9	-1.1	-0.7	-0.7	-1.1	-1.0	-1.6	-0.8	-0.8	-1.1
Hibernia (3L)	0.4	-0.1	-0.1	0.3	2.1	1.2	1.1	-0.5	-1.0	-0.8	-1.1	-0.1	-1.3	-1.5	-0.8	2.0	-0.4	-1.3
Flemish Pass (3L, 3M)	-0.3	-0.5	0.0	1.2	-0.7	-0.2	1.5	-0.6	-0.4	-1.0	-1.0	-0.2	2.2	-1.1	-1.3	-0.3	-1.0	-1.1
Flemish Cap (3M)						-0.1	0.7	0.9	-0.7	-0.8	-1.0	-0.7	1.7	-1.0	-1.1	-0.3	-1.1	-1.3
St. Pierre Bank (3Ps)	-0.6	-0.8	-0.4	-0.4	0.4	-0.6	0.1	-1.1	-1.0	-0.2	0.8	1.6	2.1	0.5	-1.2	-0.3	-0.3	0.8
SE Shoal (3NO)	1.7	0.6	-0.6	-0.7	0.0	-1.1	0.1	1.0	-0.5	-1.3	-0.2	1.7	-1.0	5.7	-1.2	-0.2	1.4	-1.1
Cabot Strait (3Pn, 4Vn)	-0.1	-1.5	-1.0	-0.6	2.3	-0.8	-0.8	1.0	0.5	0.4	-0.3	0.5	0.5	-0.3	6.0	0.6	-0.7	-1.3
NE Gulf of St. Lawrence (4RS)	-1.1	-1.1	-0.8	-1.1	0.4	1.0	-0.2	2.3	-0.3	-0.1	1.1	-0.1	0.0	-2.1	1.1	-0.9	-1.3	-2.2

Figure 14. Annual standardized scorecard anomaly indices for peak timing and duration of the spring bloom across the Newfoundland and Labrador statistical sub-regions during 1998-2015. The standardized anomalies are the differences between the annual average for a given year and the long-term mean (1998-2010) divided by the standard deviation. The numbers in the boxes are normalized anomalies. Negative anomalies for the timing indices indicate earlier/shorter blooms while positive anomalies indicate the reverse. The statistical sub-regions are sorted from northern (top) to southern (bottom) boxes. Blank grey cells indicate the fitting routine could not be achieved. Data for Flemish Cap are not available during 1998-2002.

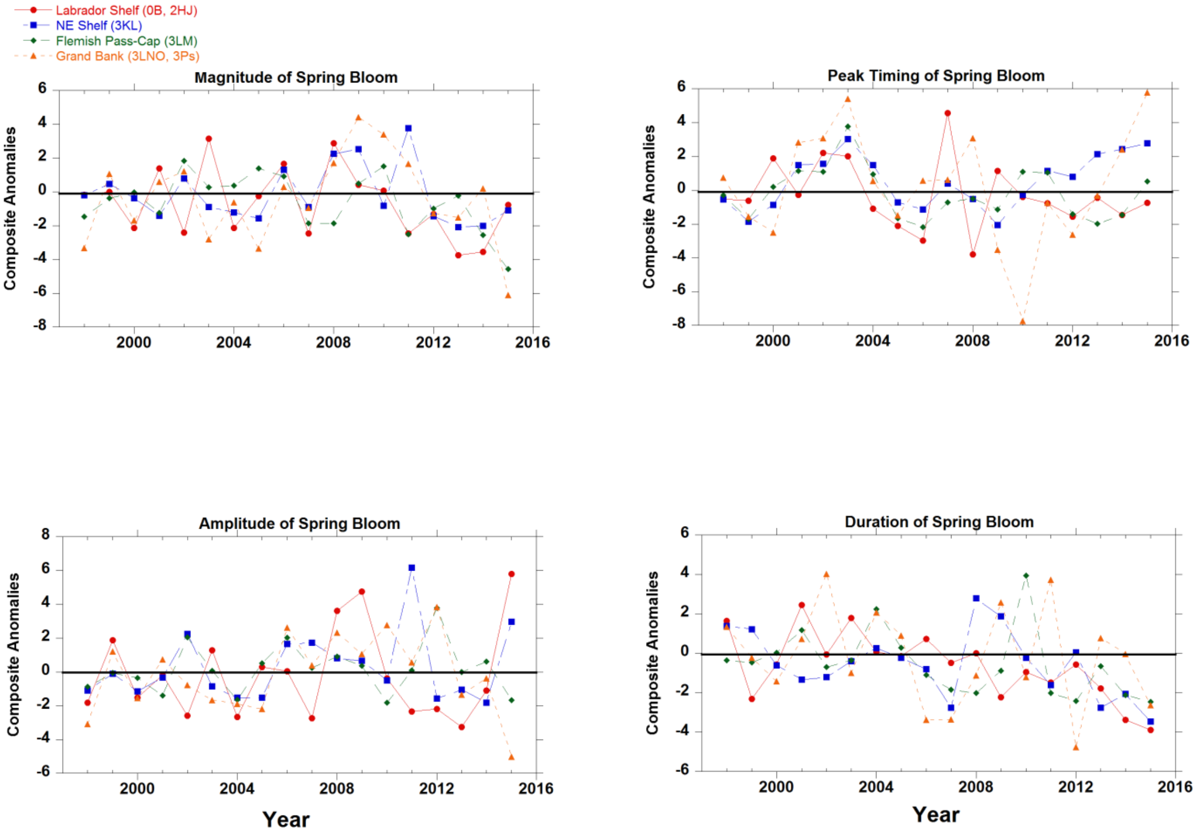


Figure 15. Composite annual anomalies across the Northern Labrador Shelf (Hudson Strait, Northern Labrador Shelf, and Hamilton Bank), the NE Newfoundland Shelf (St. Anthony Basin and the northeast Newfoundland Shelf), the Flemish Pass and Flemish Cap, and the Grand Bank (Avalon Channel, Hibernia, southeast Shoal, and St. Pierre Bank), for satellite ocean colour indices during 1998-2015. The left panels show the biomass of the spring production cycle while the right panels indicate the different timing indices. The summed standardized anomalies are the differences between the annual average for a given year and the long-term mean (1998-2010) divided by the standard deviation.

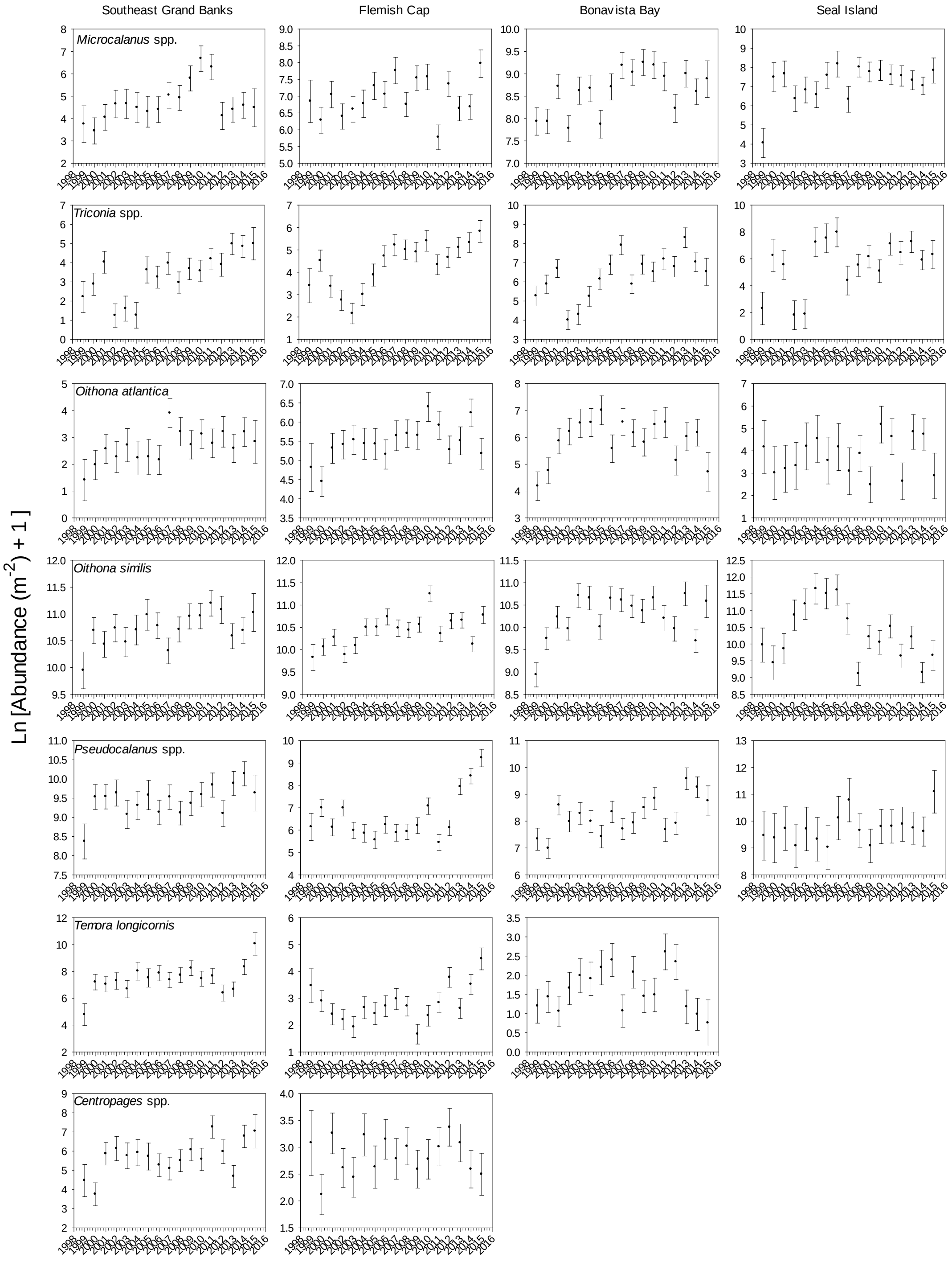


Figure 16. Seasonally-adjusted estimate of the mean abundance of small copepods from the oceanographic sections for the period 1999-2015. The error bars represent standard errors. Values from the Southeast Grand Banks are based on two occupations per year (spring, fall); values from the Flemish Cap and 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.

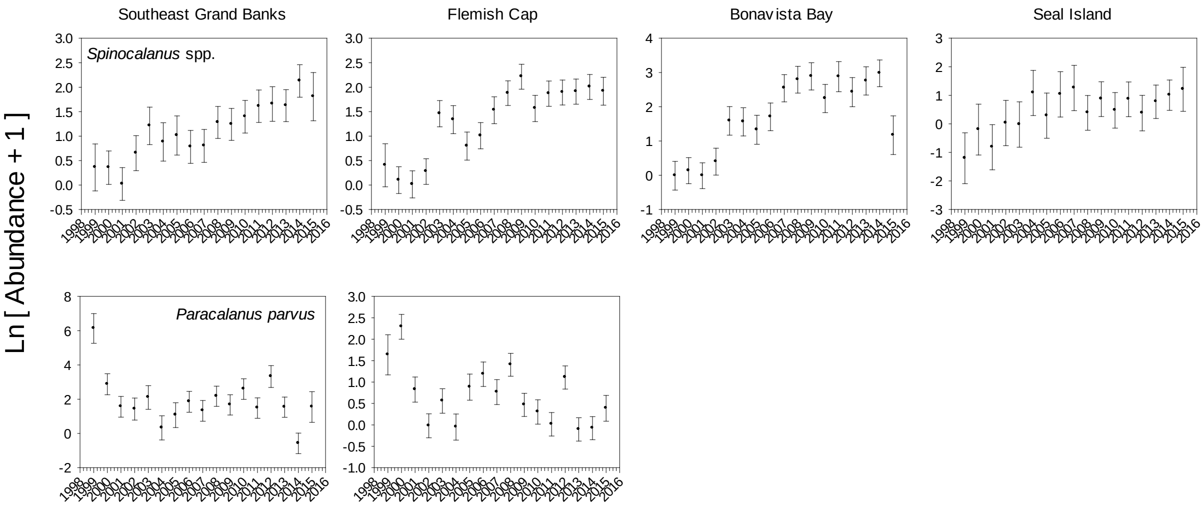


Figure 16. Continued.

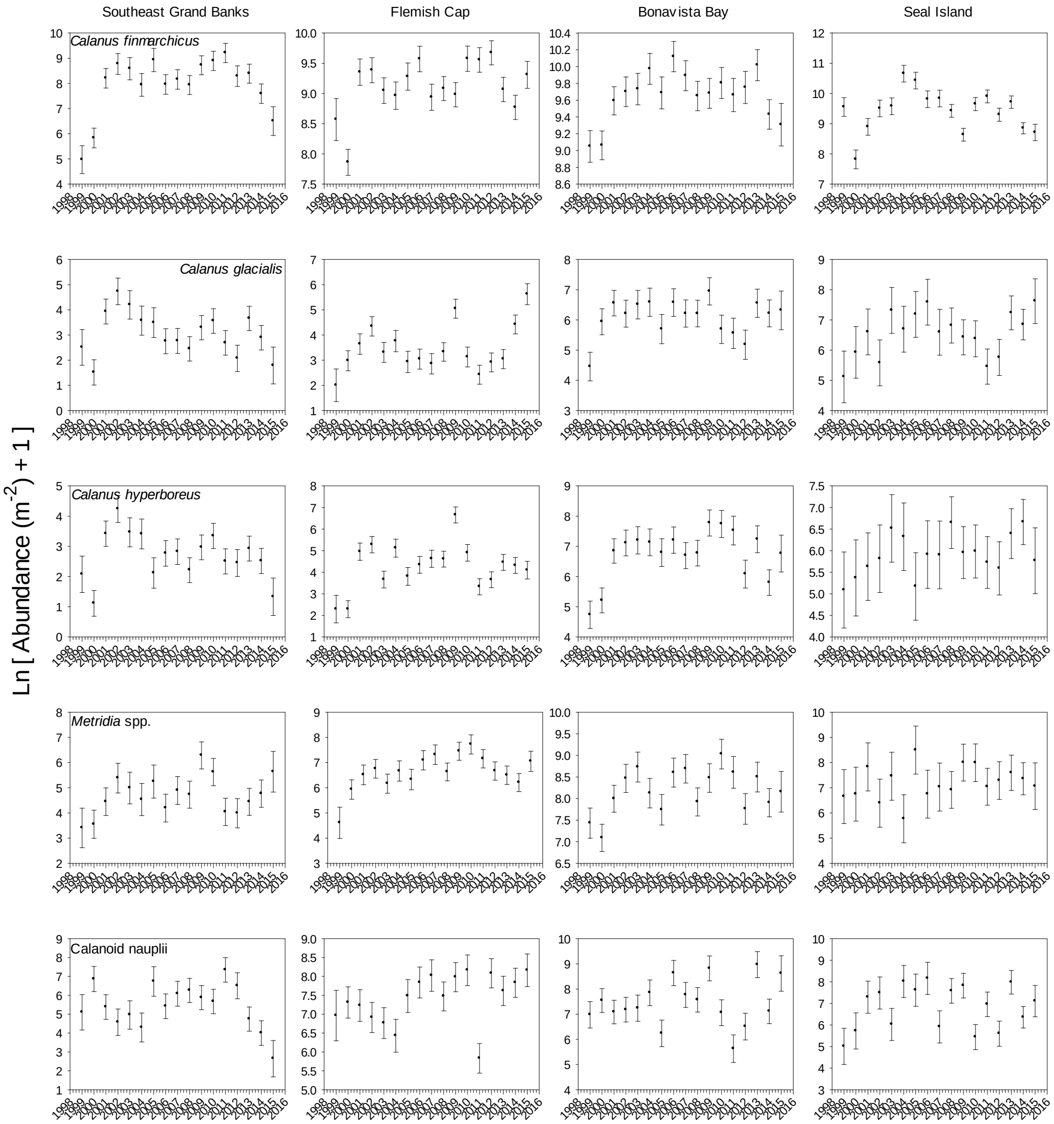


Figure 17. Seasonally-adjusted estimate of the mean abundance of large copepods from the oceanographic sections for the period 1999-2013. The error bars represent standard errors. Values from the Southeast Grand Banks are based on two occupations per year (spring, autumn); values from the Flemish Cap 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.

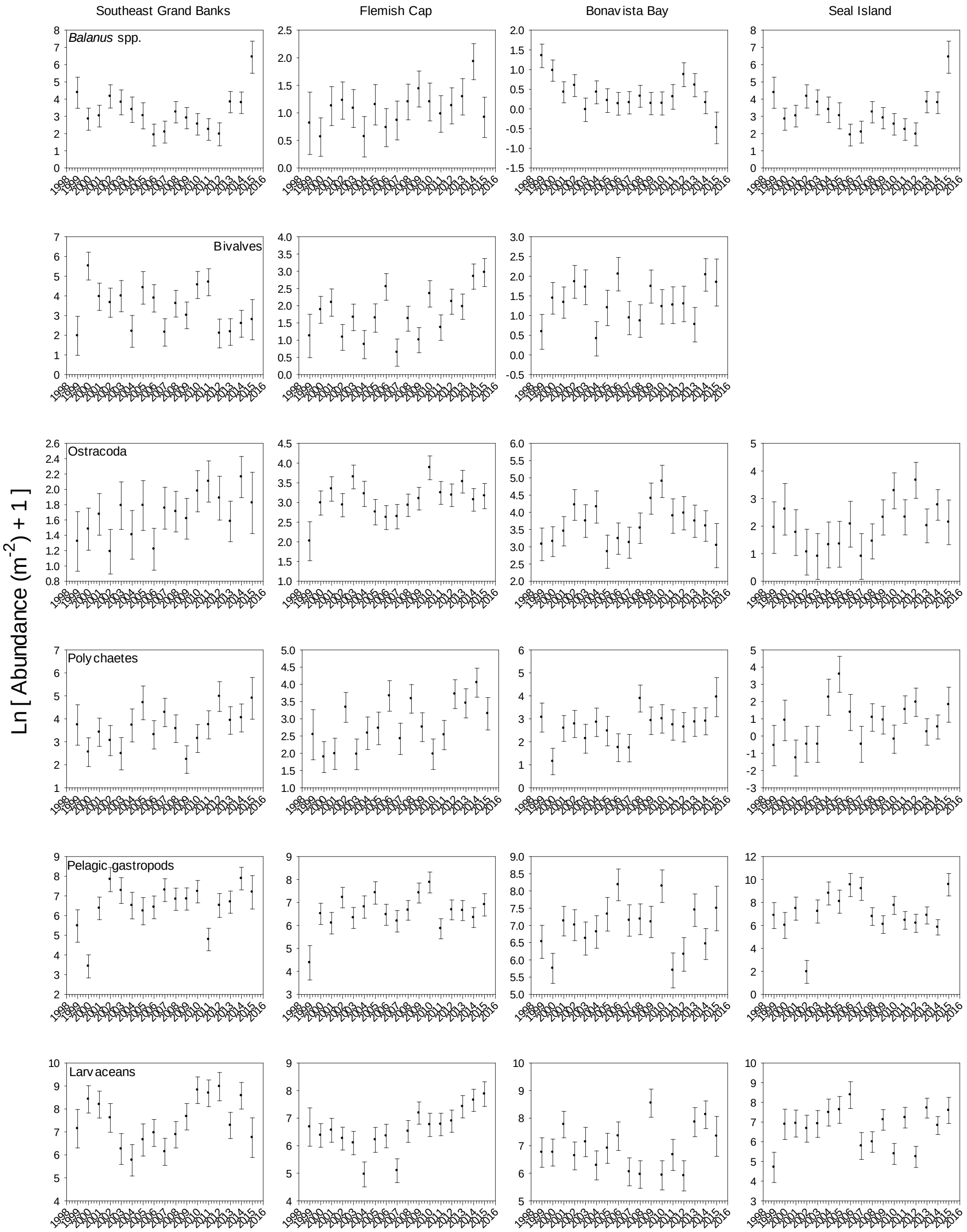


Figure 18. Seasonally-adjusted estimate of the mean abundance of meroplankton and other selected taxa from the oceanographic sections for the period 1999-2013. The error bars represent standard errors. Values from the Southeast Grand Banks are based on two occupations per year (spring, fall); values 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.

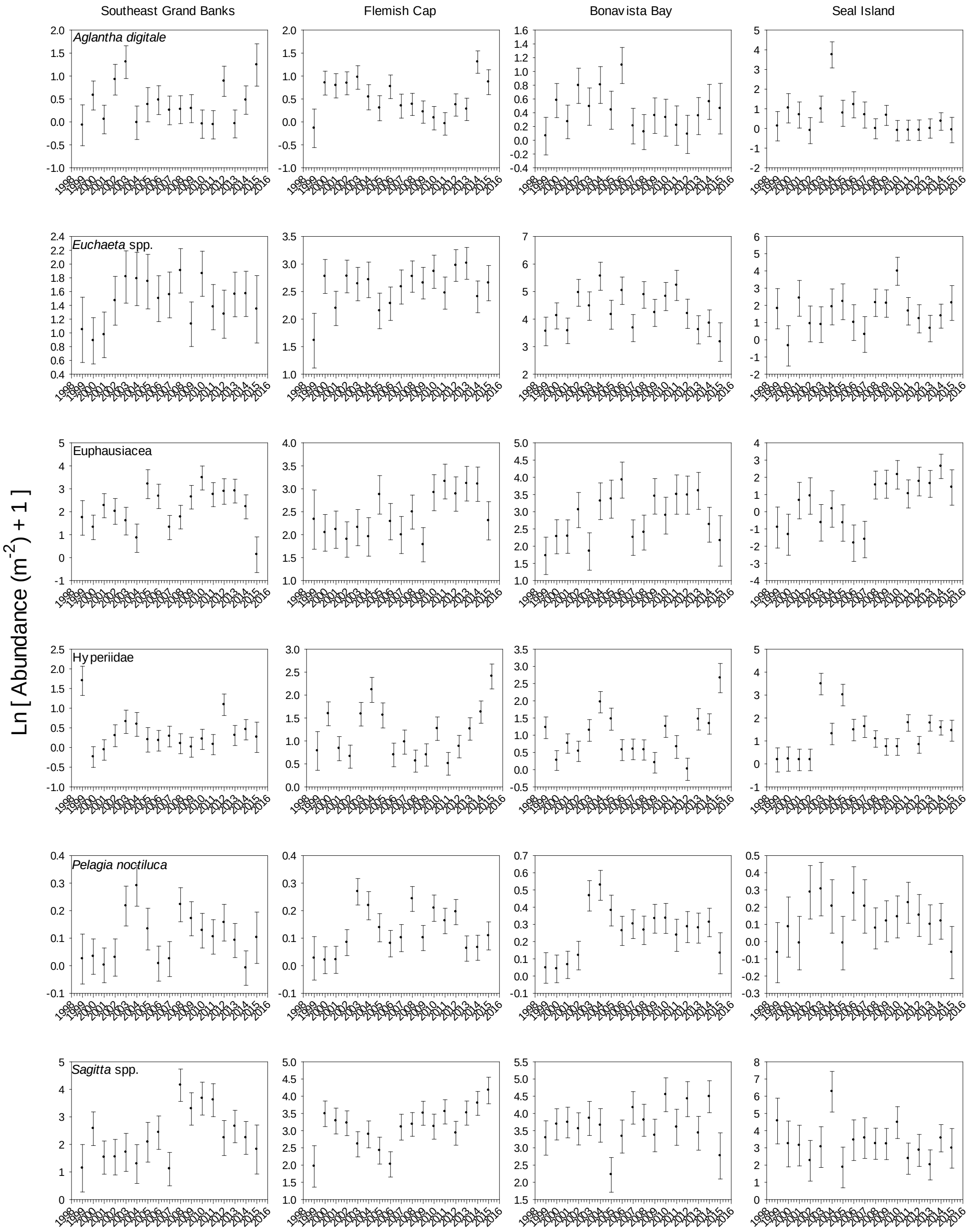


Figure 19. Seasonally-adjusted estimate of the mean abundance of carnivorous zooplankton from the oceanographic sections for the period 1999-2013. The error bars represent standard errors. Values from the Southeast Grand Banks are based on two occupations per year (spring, fall); values from the Flemish 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.

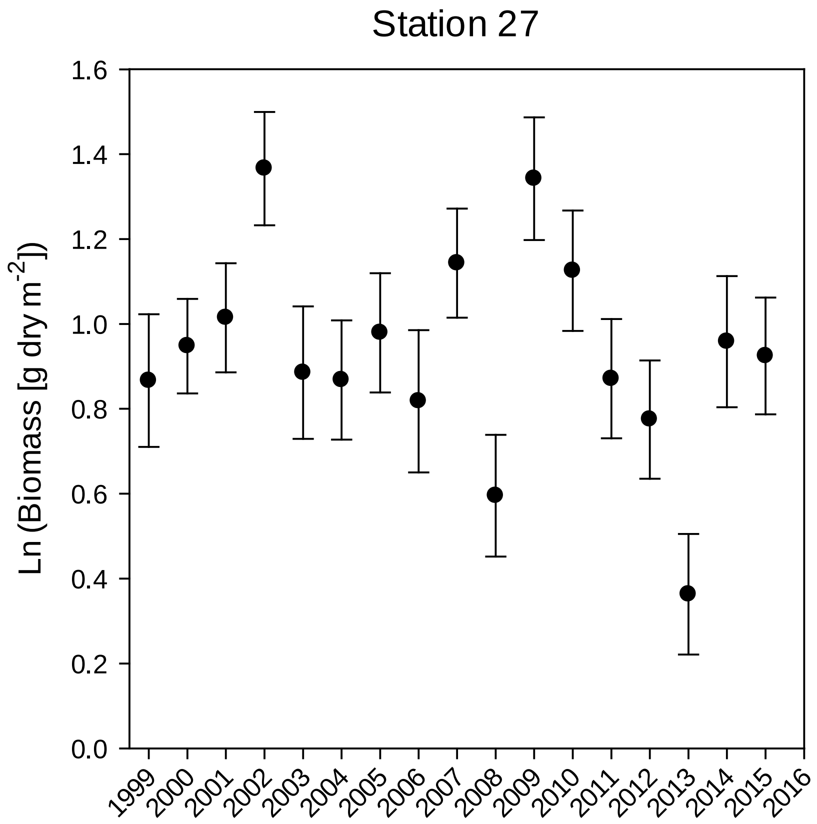


Figure 20. Seasonally-adjusted estimates of the mean biomass of eight dominant copepod species from S27 for the period 1999-2013. The error bars represent standard errors.

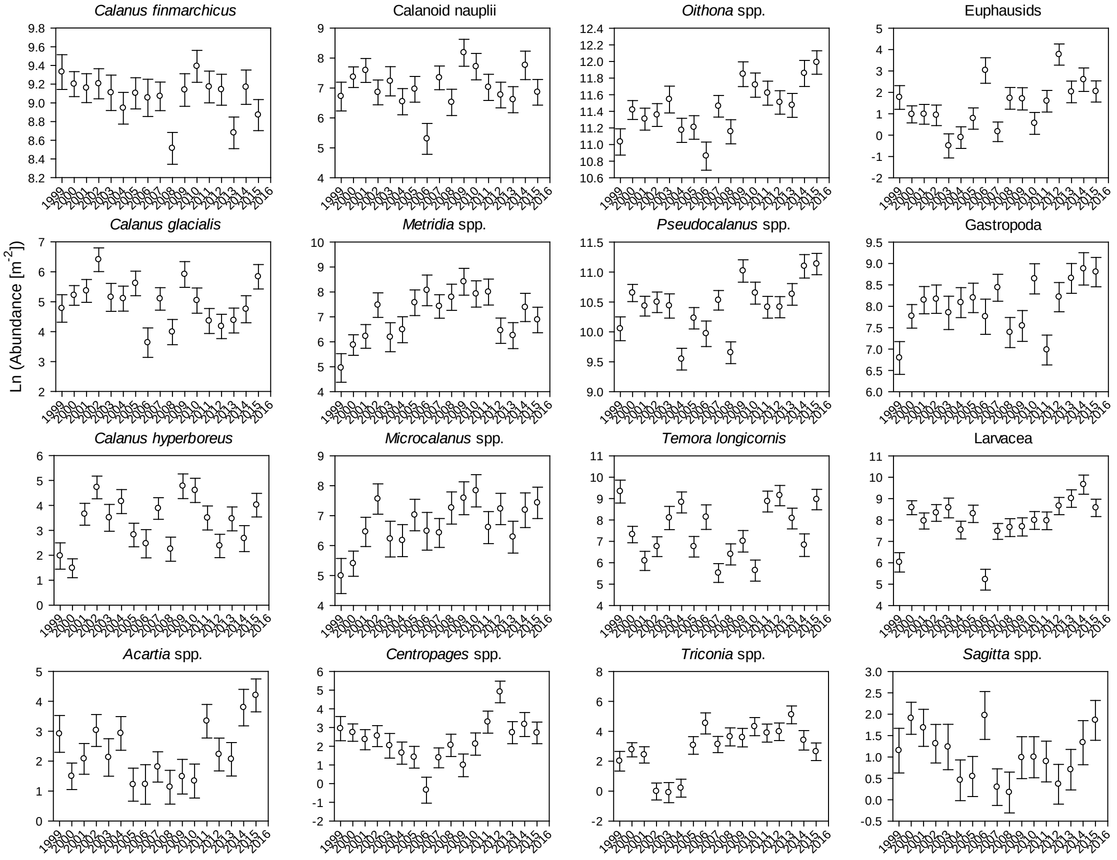


Figure 21. Seasonally-adjusted estimate of the mean abundance of twelve dominant zooplankton taxa from S27 for the period 1999-2013. The error bars represent standard errors.

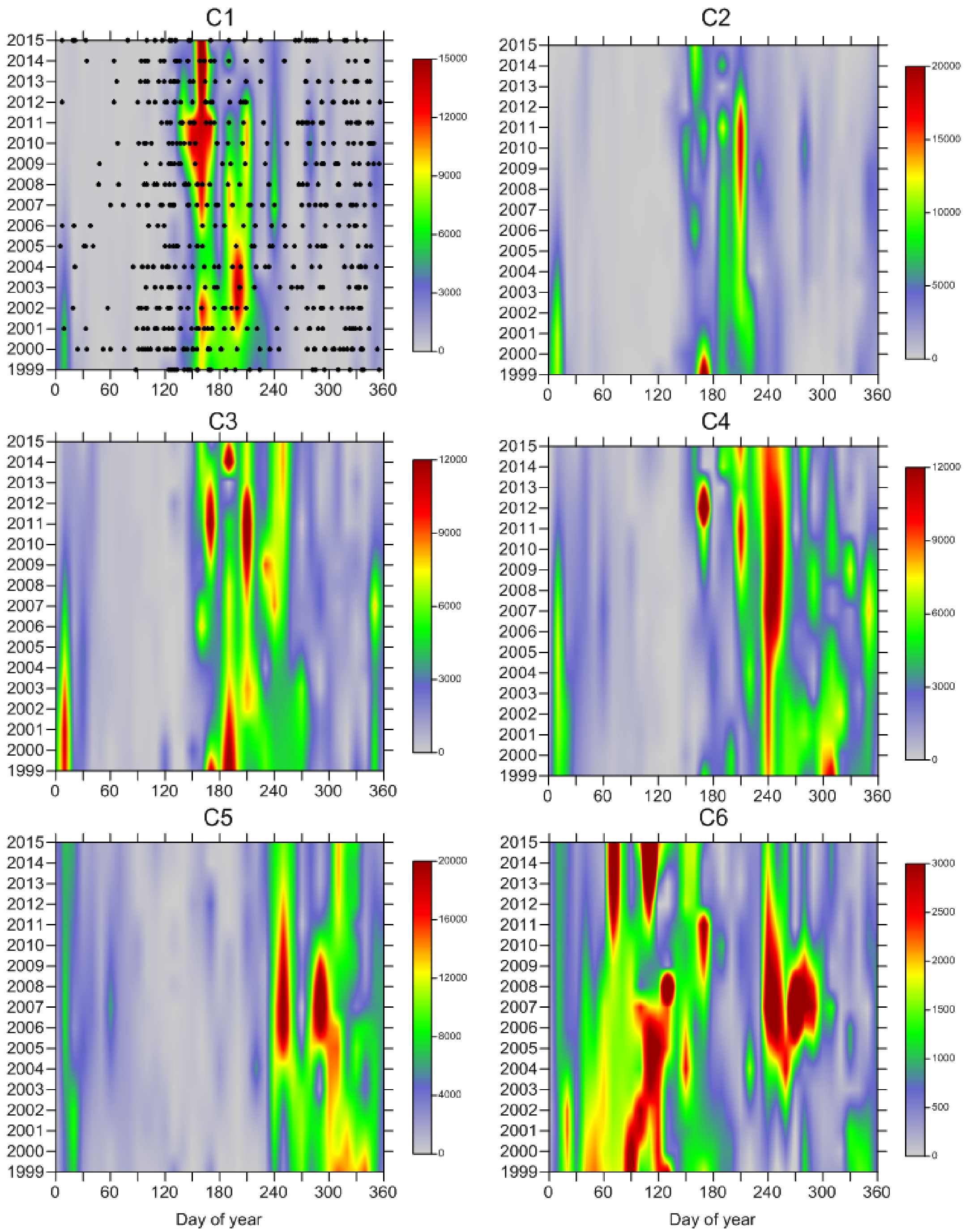


Figure 22. Seasonal cycle of abundance (number m^{-2}) of stage CI to CVI copepodites of Calanus finmarchicus for the period 1999-2013. The circles in the upper left panel reflect sampling dates.

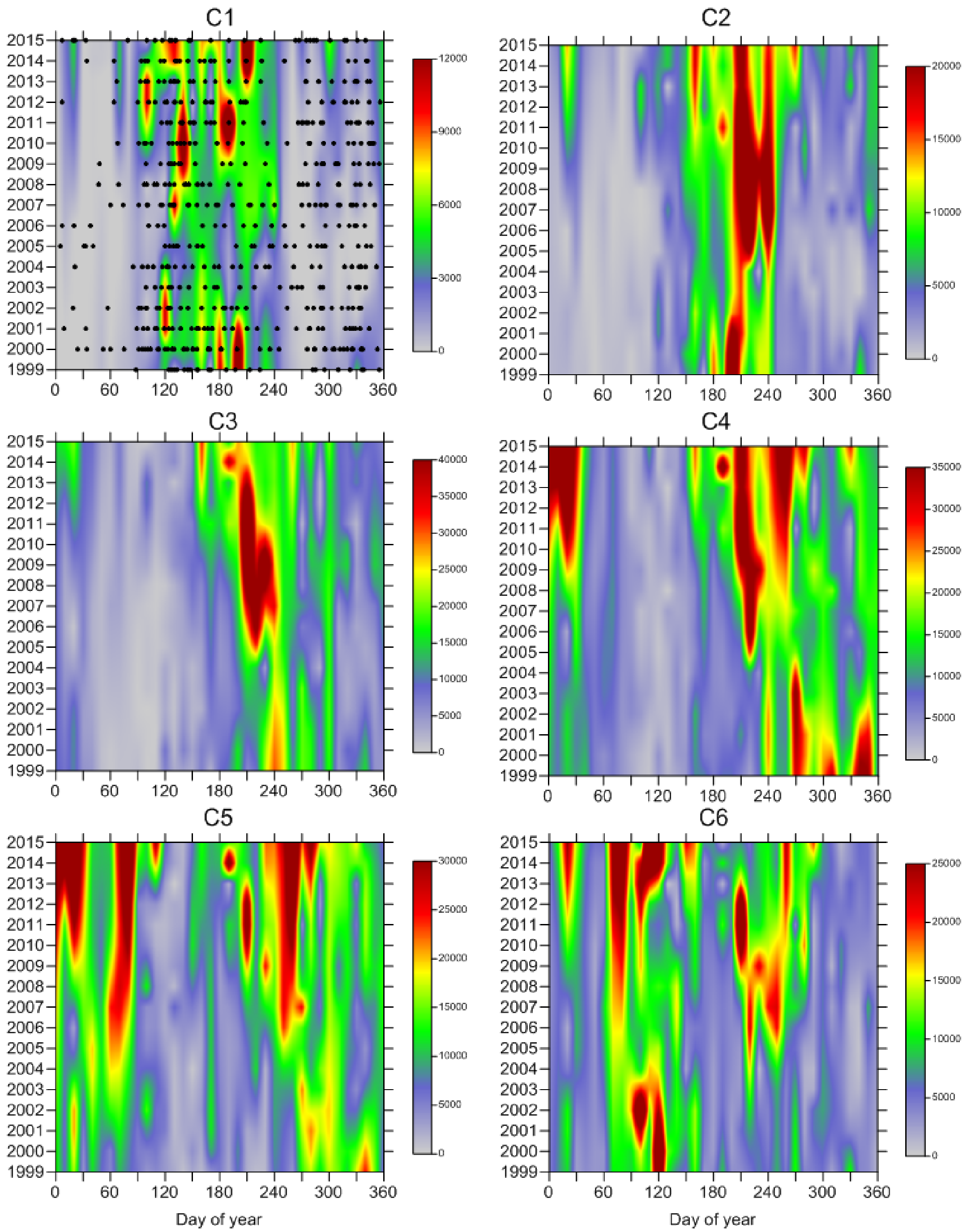


Figure 23. Seasonal cycle of abundance (number m^{-2}) of stage CI to CVI copepodites of Pseudocalanus sp. for the period 1999-2013.