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The 1990s a Unique Decade for Plankton Change in the Northwest Atlantic

Les années 1990 : une décennie unique de changements dans le plancton dans l'Atlantique Nord-Ouest

D. Sameoto

Biological Oceanography Section
Ocean Sciences Division
Bedford Institute of Oceanography Fisheries and Oceans Canada
Box 1006
Dartmouth, NS
B2Y 4A2

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Abstract

Continuous Plankton recorder data collected between Iceland and New England between years 1959 and 2001 showed that the 1990s decade was one in which large changes in the abundance of phytoplankton and zooplankton occurred. Total diatoms and dinoflagellates increased in the 1990s in the western North Atlantic and along the Scotian shelf, whereas the abundance of *C. finmarchicus* stages 1 to 4 decreased on the western North Atlantic and Scotian Shelf zones. In the eastern North Atlantic (east of longitude 45°W), the abundance of *C. finmarchicus* stages 1 to 4 did not decline in the 1990s. In the 1990s the yearly fluctuations in the phytoplankton color index were similar in the western North Atlantic, Scotian Shelf and Georges Bank zones. However, the pattern of yearly change on the eastern North Atlantic was lower and different from those seen on the other zones. The changes observed in the 1990s were due to changes in abundance of the taxa in the early and late months of the year with little change seen during the summer and early fall months. January to March 1998 and 1999 had the largest positive diatom deviations from the monthly means in the 1991 to 2001 decade, and 1999 was a year of exceptionally high haddock recruitment on the Scotian Shelf.

Résumé

Les données d’enregistrement continu du plancton recueillies de 1959 à 2001 entre l’Islande et la Nouvelle-Angleterre révèlent que les années 1990 étaient une décennie pendant laquelle des changements importants dans l’abondance de phytoplancton et de zooplancton se sont produits. L’abondance totale de diatomées et de dinoflagellés a augmenté dans l’Atlantique Nord-Ouest et le long du plateau néo-écossais, tandis que l’abondance des stades 1 à 4 de *C. finmarchicus* a diminué dans cette partie de l’Atlantique et sur le plateau néo-écossais. Par contre, dans l’Atlantique Nord-Est (à l’est de 45^{o} de longitude ouest), l’abondance des stades 1 à 4 de ce copépode n’a pas diminué. Les fluctuations annuelles de l’indice de coloration phytoplanctonique pendant cette décennie étaient semblables dans l’Atlantique Nord-Ouest, sur le plateau néo-écossais et sur le banc Georges, alors qu’elles étaient moins marquées bien que différentes dans l’Atlantique Nord-Est. Les changements observés sont imputables à des changements dans l’abondance des taxons pendant les premiers et les derniers mois de l’année, peu de changements ayant été observés en été et au début de l’automne. Les plus fortes augmentations de l’abondance de diatomées par rapport aux moyennes mensuelles pour la décennie entre 1991 et 2001 se sont produites de janvier à mars en 1998 et 1999. De plus, 1999 était une année de recrutement exceptionnellement élevé de l’aiglefin sur le plateau néo-écossais.

Introduction

The decade of the 1990s was a period of major collapse of several ground fish species in the western Canadian Atlantic and it was also a time of significant ocean temperature change in the Atlantic region. In 1999 the haddock stocks on the eastern and central region of the Scotian shelf had exceptional recruitment. Haddock spawn in the months of January to July with the peak spawning occurring on the Scotian shelf in April (Leim and Scott 1966). Haddock larvae feed on microzooplankton and phytoplankton in the their early life stages (Kane 1984). This study examines the changes in plankton that occurred in the western Atlantic between 1960 and 2001. The study also looks in detail at changes in plankton abundance that occurred on the Scotian shelf during the 1991 to 2001 decade for evidence that these changes may be associated with the high requirement of haddock and cod larvae in 1998 and 1999.

The longest time series of data describing trends in phytoplankton and zooplankton species concentrations northwestern Atlantic on the Canadian eastern continental shelf is the Continuous Plankton Recorder Survey (CPR) collected for The Sir Alister Hardy Foundation of Plymouth, England. These data were collected between 1959 to the present, with a break of a number of years from 1976 to 1991, along two transect lines, the Z-line running between Iceland and Newfoundland and the E-line between Newfoundland and the east coast of the United States of America. The CPR is towed by commercial and weather ships at an average depth of approximately 6.7 m (Hays and Warner 1993) at speeds of up to 20 knots. The CPR has a mouth opening of 1.25 cm^2 and a filtering mechanism inside the vehicle that collects samples of phytoplankton and zooplankton on a slowly moving band of bolting silk with a mesh size of about 285 x 315 µm. The sample is then covered with a second silk and wound onto a spool in a tank of formalin and preserved. The CPR is towed at regular monthly intervals along generally fixed shipping routes.

Methods

CPR data from eight taxonomic groups, including the phytoplankton color index, total dinoflagellates, total diatoms, total copepods, *Calanus finmarchicus* stages 1 – 4, *C. finmarchicus* stages 5 – 6, *Paracalanus/Pseudocalanus*, and total euphausiids were transformed to $\log_{10}(x+1)$ to normalize the variance before any statistical analyses were calculated. A least squares cubic spline smoother was calculated using the program S-plus 6 (MathSoft 1999) to demonstrate trends in abundance with time. The smoother relies on the data to specify the form of the model and the curve is fit to data points locally so that any point on the curve depends only on observations at that point and a specified range of neighboring points. The smoother gives a more realistic representation of the data than a polynomial regression. Climatological means were calculated for the taxa for each month of the year using a time period of 1961 to 2001 and also a period of 1991 to 2001. Deviations from the monthly means were calculated for the 1991 to 2001 period by subtracting the monthly values for each year from the climatological mean for each of the months. These monthly deviations were then contoured using the contour program in S – plus 6.

These data were subdivided into five geographic zones, the eastern Atlantic (the zone between longitude 45° W and Iceland), the western Atlantic (between longitude 45° W and Newfoundland), the eastern Scotian Shelf (between longitude 57° W and 62° W), the western Scotian Shelf (between longitude 62.01°W and 66° W) and Georges Bank (longitude >66.01° W to 70.00° W) (Fig. 1).

Results

The CPR data in the 1991 to 2001 decade showed major changes in abundance of phytoplankton and zooplankton on both the E and Z lines compared to levels seen between 1961 and 1974 on the E line and 1959 to 1985 on the Z line. The phytoplankton color index on the Z line had an increasing trend from 1991 to 2001; whereas the color index on the E line had a large increase in 1992 after which time it remained relatively stable at this level for most of the years 1993 to 2001 (Fig. 2).

The major zooplankton taxon on both lines was *Calanus finmarchicus* stages 1 to 4. Its yearly means did not show a trend on the Z line and values in the 1991 – 2001 period were similar to the climatological mean.By contrast, on the E line *C. finmarchicus* stages 1 to 4 yearly means had a decreasing trend between 1994 and 2001 (Fig. 2).

Comparison of Taxa in Five Geographic Zones during 1991 to 2001

Yearly means between 1991 and 2001 for the phytoplankton color index, total diatoms, total dinoflagellates, *C. finmarchicus* stages 1 to 4, *C. finmarchicus* stages 5 and 6, total copepods and total euphausiids were plotted for the five geographic zones (Figs. 3 and 4). The yearly variation of the phytoplankton color index was similar in four of the five zones and appeared to be synchronized. The eastern Atlantic zone line did not have the large yearly fluctuations seen in the other four zones and its values were much lower (Fig. 3). The phytoplankton color index is primarily the result of the sum of chlorophyll from diatoms and dinoflagllates collected on the silk. The yearly means of total diatoms and total dinoflagellates did not show the same degree of fluctuation seen in the color index (Fig. 3). The were no trends in the color index or total dinoflagellate data, whereas the total diatoms showed an increasing trend from 1991 to 1999 on the Scotian shelf and Georges Bank zones. After 1999 the diatom levels in these zones decreased. The yearly means of the diatoms and dinoflagellates were consistently lower in the eastern Atlantic zone than in the other four zones.

C. finmarchicus stages 1 – 4 on the Scotian shelf and Georges Bank showed a downward trend between 1991 and 1998, and after 1998 the means on the Scotian Shelf increased in value. The means in the two Atlantic zones showed no trends (Fig. 4). *C. finmarchicus* stages 5 & 6 and the total copepods did not have a trend in their yearly means during this period in any of the five zones. The total copepod levels on both Z line zones were generally lower than levels on the E line zones. The total euphausiids means had a strong downward trend on both the western and eastern zones of the Atlantic, whereas the zones of the E line showed no trend in the euphausiid means (Fig. 4).

Monthly Changes in Taxa Abundance on the Scotian Shelf

To determine in which months of the year changes occurred in the abundance of eight taxa during the 1990s, monthly data for each year were analyzed in detail for the period 1961 to 2001. The taxa analyzed were the phytoplankton color index, total diatoms, total dinoflagellates, total copepods, *C. finmarchicus* stages 1 to 4, *C. finmarchicus* stages 5 and 6, *Pseudocalanus/ Paracalanus spp.* and total euphausiids. The monthly values for each year plus the monthly means are shown in Figs. 5 and 6. The phytoplankton color index increased in the 1990s occurred primarily during January to April, with slightly higher values in the months September to December. There were no obvious increases in the 1990s during months May to August. In the 1990s the total diatom increase was greatest during January to March, and the total dinoflagellate increase was highest in the months February to April (Fig. 5).

The total copepod abundance in the 1990s was above the climatological mean in most years during March and April, whereas during the other months it was similar to or below the means (Fig. 6). In the early 1990s the numbers were above the mean during the first four months of the year. The numbers declined during February to April from 1992 to 1999. This decline was not obvious in the other months of the year. *C. finmarchicus* stages 1 to 4 in the 1990s were above the climatological mean in April in all but one year, 1999, whereas it was usually below the means during the other months. *C. finmarchicus* stages 5 and 6 were generally below the climatological means in all months except April and May when it was similar to the monthly means. The *Pseudocalanus/Paracalanus* taxon was generally above the monthly means in January, March and April in the 1990s (Fig. 6). The total euphausiid abundances were usually below the monthly means in February to April and July to September (Fig. 6).

Comparison Between the Eastern and Western Scotian Shelf Zones

The taxa on the eastern and western zones of the Scotian shelf were compared monthly for years 1991 to 2001 to detect any signal in the plankton data that may help provide information to explain why there was exceptional haddock and good cod recruitment in 1999 on the eastern and central Scotian shelf. Haddock reproduce in the spring, therefore if there was a connection between high recruitment and plankton it probably occurred in the first half of the year. The phytoplankton color index in the two zones showed similar patterns of abundance during different months, particularly between January to April (Fig. 7). In 1998 the color index was exceptionally high in the eastern Shelf between February and April plus high during March on the western Scotian Shelf. The levels of diatoms were above the mean in both regions in March and dinoflagellates were above the mean in March and April. The total copepods and *Pseudocalanus* / *Paracalanus* species were above the mean in March 1998 (Table 1 and Fig. 7 & 8). The large number of taxa above the climatological monthly mean in March 1998, indicated that this was an exceptional month for plankton on both the eastern and western Shelf regions.

January 1999 was a unique month in that four of the five taxa, the exception being *C. finmarchicus* stages 1 – 4, were above their climatological means (Table 1) and the diatom and dinoflagellate values were among the highest recorded in all Januarys between 1961 and 2001 (Fig. 5).

Monthly values and deviations from Monthly Means, 1991 to 2001

The yearly monthly values between years 1991 to 2001 for the phytoplankton color index, total diatoms, total dinoflagellates and total copepods on the eastern and western Scotian shelf combined were contoured (Fig. 9). The spring bloom as indicated by the phytoplankton color index contours, occurred progressively earlier between 1991 and 1999, after 1999 the bloom weakened. However, the total diatom contours in the spring remained high from 1991 to 2001 and peaked about a month earlier in 1999 than in 1992 (Fig. 9). The total dinoflagellate contours did not show the spring bloom occurring earlier in the year during this decade and high values appeared to occur only every second or third year. The contours for total copepods were highest in the early 1990s and did not show a trend towards occurring earlier as was seen for the color index and total diatoms.

The deviations from individual monthly means for the phytoplankton color index was greater than zero between February and May 1998 and from January to March in 1999 (Fig. 9). February 1998 and January 1999 had the highest positive deviations for these months in the entire data series. January and February in 1998 and 1999 also had the highest values for the total diatom deviation, whereas the dinoflagellate deviation for these months was not exceptionally high. The total copepod deviation index during January and February 1998 and 1999 was close to or below zero, this indicated that these months did not have unusually high levels of copepods compared to the earlier years (Fig. 9). The highest total copepod deviations in the early months occurred in 1993 when the index was above zero from January to June. In 1993 deviations for color index and total diatoms were below or near zero for the first six months of the year. The dinoflagellate deviation index on the other hand was above zero for five of the six first months of 1993 (Fig. 9).

Discussion

Phytoplankton color index yearly means on the entire Z line had a large increase between 1986 and 1991 and it continued to increase during the years 1991 to 2001. The yearly means of the color index on the E line from the eastern edge of the Scotian shelf to the southern region of Georges Bank did not increase until 1992 and then the values fluctuated about this new high value until 2001. The Z line color index, total diatoms and dinoflagellates analyzed for the two geographic areas the eastern and western Atlantic zones showed major differences in yearly means. The eastern zone of the Z line had a significantly lower mean of these three taxa than did the western zone. The index in the western Atlantic zone was similar in value to those seen for the E line zones. The total diatom and dinoflagellate means in the western Atlantic were within the yearly variation seen on the E line but were at the lower range of the values for the Scotian shelf. The means for diatoms and dinoflagellates on the eastern Atlantic were significantly lower than the western Atlantic zone and the dinoflagellate means were lower than those of the diatoms.

This suggests that the physical and or chemical factors that caused the changes in the index were likely similar on the western Atlantic and the E line zones. The western Atlantic and E line zones are all subject to the influence of the Labrador Current, whereas the eastern Atlantic zone is not. Therefore, we should look for changes in the Labrador Current during the late 1980s and early 1990s for a possible explanation for the changes we see in the color index and abundances of diatoms and dinoflagellates. Sameoto (2001) found that it was possible to explain between 21 and 42% of the variance of multiple regressions between the color index, total diatoms and dinoflagellates and physical indices of temperature, stratification and storm, defined as the annual standard deviation of wind stress. In the 1991 to 1998 period Sameoto (2001) found that the temperature and stratification indices were higher and the storm index was lower than in the 1960 to 1970s period in the region of the western Atlantic and E line zones. It would be informative to know if these same indices in the eastern Atlantic zone had changed in the 1990s compared to the 1960 to 1980 period.

The color index in the 1990s showed large regular fluctuations that appeared to be the result of a high abundance of dinoflagellates every two or three years superimposed on the fluctuating yearly values of the diatoms. Whether the periodic high spring values of dinoflagellates are due to chance or the result of some periodic physical event is unknown. It appeared that both diatoms and dinoflagellates were influenced by the same forces in this decade.

The yearly mean values between 1960 and 2001 for *C. finmarchius* stages 1 to 4 on the entire Z line from Iceland to Newfoundland fluctuated randomly around the climatological mean and did not show a sudden change in value or trend. Whereas, the mean of *C. finmarchicus* stages 1 to 4 on the E line from the eastern edge of the Scotian shelf to the southern region of Georges Bank had a large decrease in value after 1993 and continued to gradually decrease until 2001. The western Atlantic zone had higher yearly means of *C. finmarchicus* stages 1 to 4 and stages 5 and 6 during the 1991 to 2001 decade than the other zones. The *C. finmarchicus* stages 5 and 6 means from the eastern Atlantic zone for stages 5 and 6 were similar to the western Atlantic zone. The zones of the E line had similar yearly means for *C. finmarchicus* stages 1 to 4 and stages 5 and 6. The total copepod yearly means were much higher on the E line zones than on the Z line zones. This showed that *C. finmarchicus* has a greater importance relative to other species on the Z line than on the E line, other species of copepods such as *Pseudocalanus/Paracalanus spp*. were more abundant on the E line. The total euphausiids on both zones of the Z line declined in the 1990s whereas; their means were relatively stable on the zones of the E line.

The largest significant changes in abundance of the phytoplankton taxa on the E line in 1991 to 2001 occurred during the first half of the year with the largest monthly increases in the months January to March. This indicates that the physical and or nutrient factors responsible for the increases seen in the 1990s were occurring primarily in the early part of the year or late in the previous year.

In the 1990s total copepod and *C. finmarchicus* stages 1 to 4 monthly values were significantly higher during March and April than in the earlier years, the other months were not significantly different or were below the values seen in the 1960s to 1970s period. The major difference in the monthly abundance of *C. finmarchcius* stages 5 and 6 between the early years and the 1990s was the low numbers between June and December in the 1990s. This suggested a failure of the species to produce a significant second generation in the fall.

Cod and haddock recruitment was high in 1998 and 1999 and both these fish spawn in the spring on the Scotian Shelf. The young larvae feed on microzooplankton and probably phytoplankton in their early life history. The plankton data from the 1991 to 2001 period on the Scotian shelf showed that the levels of diatoms were above the monthly means from January to March in 1998 and 1998. The diatom bloom occurred earlier in these two years than it did in other years in that time period. The only zooplankton taxa that was above the monthly mean in these years was *Pseudocalanus/Paracalanus* spp. and it had exceptionally high values in January of 1999. Platt et al. (2003) compared the link between haddock recruitment on the Scotian shelf and local dynamics of the spring bloom of phytoplankton as measured from ocean color satellite data. They found that the timing of the spring bloom accounted for 65% of the interannual variance in the abundance of the 0-group haddock, and that the higher 0-group abundance was associated with an earlier spring bloom. The mechanism by which such a relationship occurs (if it is real) is unknown. The CPR sampler does not sample the microzooplankton that are the main source of food for young larvae. It is possible that an early phytoplankton bloom results in a large increase in the population of microzooplankton earlier in the year thereby increasing the chances of survival of larvae from the early spawners. The observation that there was no obvious connection between *C. finmarchicus* abundance and the high fish requirement implies little connection between the two. McLaren (et al. 1997) reported that cod larvae on the Scotian shelf in the fall fed predominately on copepodids of *Pseudocalanus.* If haddock larvae showed the same feeding preference then it is possible that feeding conditions in January of 1999 were particularly favourable since the abundance of *Pseudocalanus/Paracalanus* was high for this month.

The correspondence between the very high requirement of haddock and the exceptionally early diatom blooms in these years appears to be more than a coincidence, however only a much longer data series of both recruitment and plankton data will tell if these two events are related.

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Table 1. Months in 1998 and 1999 with above normal values of taxa on the eastern and western Scotian shelf.

1998

	January		February		March		April		May		June	
	E	W	E	W	E	W	E	W	E	W	E	W
Color index			x		x	x	x					
Diatoms	x		x		x	x						
Dinoflagellates	x				x	x	x	x		x		
Total copepods					x	x						
C. finmarchicus 1-4												
Pseudo\Paracalanus					x	x						
1999												
Color index	x	x		x		x						
Diatoms	x	x	x		x	x						
Dinoflagellates	x	x		x								
Total copepods	x	x										
C. finmarchicus 1-4							x					
Pseudo\Paracalanus	x	x										

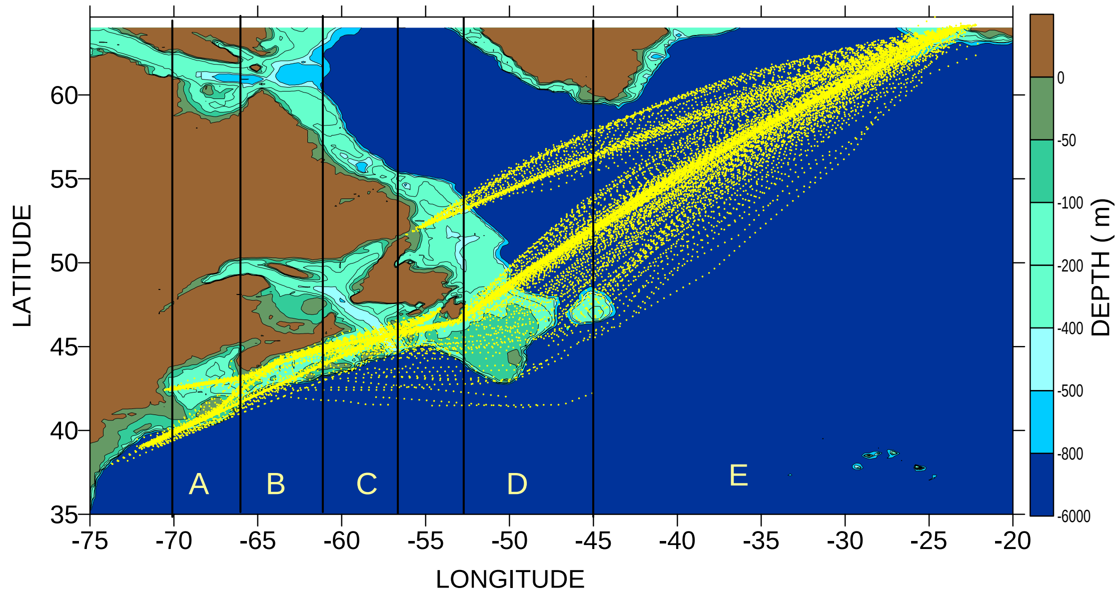


Fig. 1. CPR station position (yellow dots) for years 1960 to 2001 for the E line (A,B and C) and Z line (D and E). Vertical lines show demarcations between the zones. A- Georges Bank, B- western Scotian shelf, C-eastern Scotian shelf D-western Atlantic and E- eastern Atlantic. Data from station beyond the 200m contour were not included in the A, B and C zones.

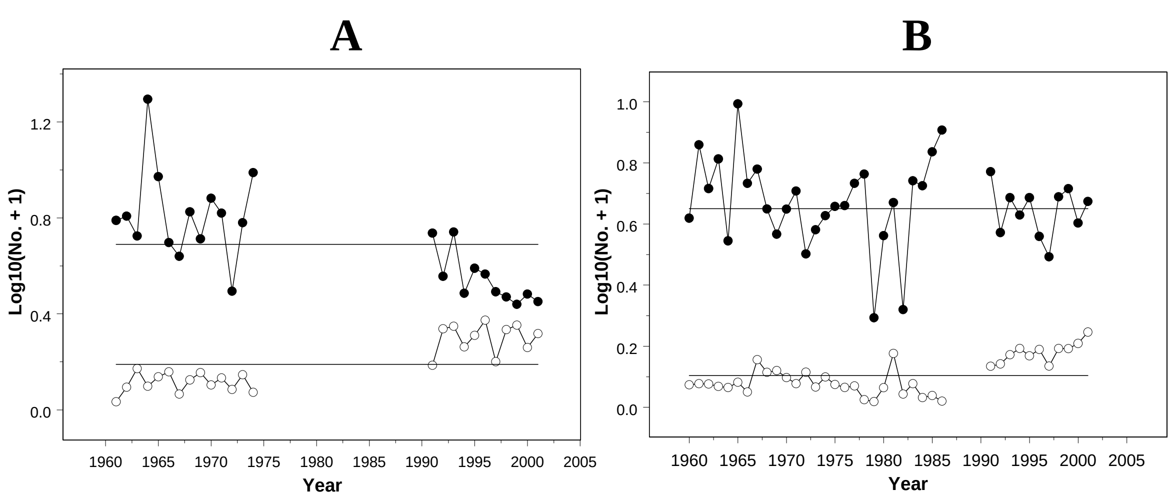


Fig. 2. Yearly means for Phytoplankton color index (open circles) and C. finmarchicus stages 1 to 4 (solid dots) for the E line (A) and Z line (B). The horizontal lines represent the climatological means for the entire data sets.

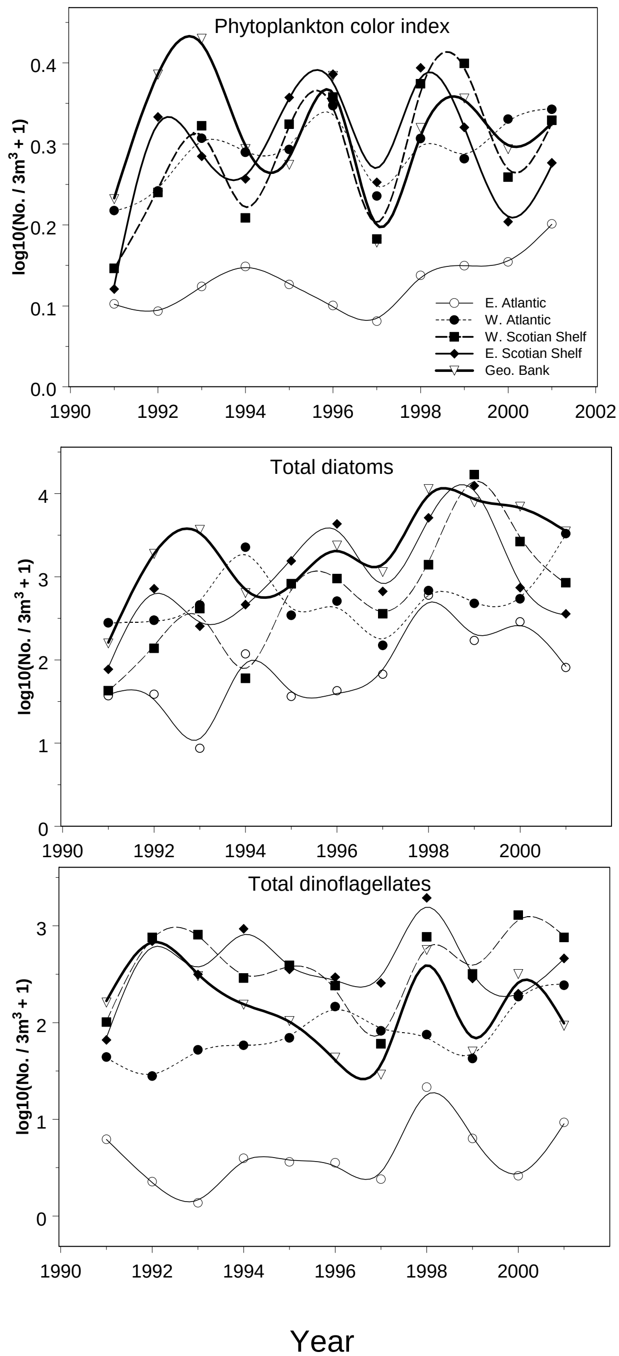


Fig. 3. Yearly means and spline smoothers for phytoplankton color index, total diatoms and total dinoflagellates on the eastern Scotian shelf, western ScotianGeorges Bank, western Atlantic and eastern Atlantic zones for years 1991 to 2001.

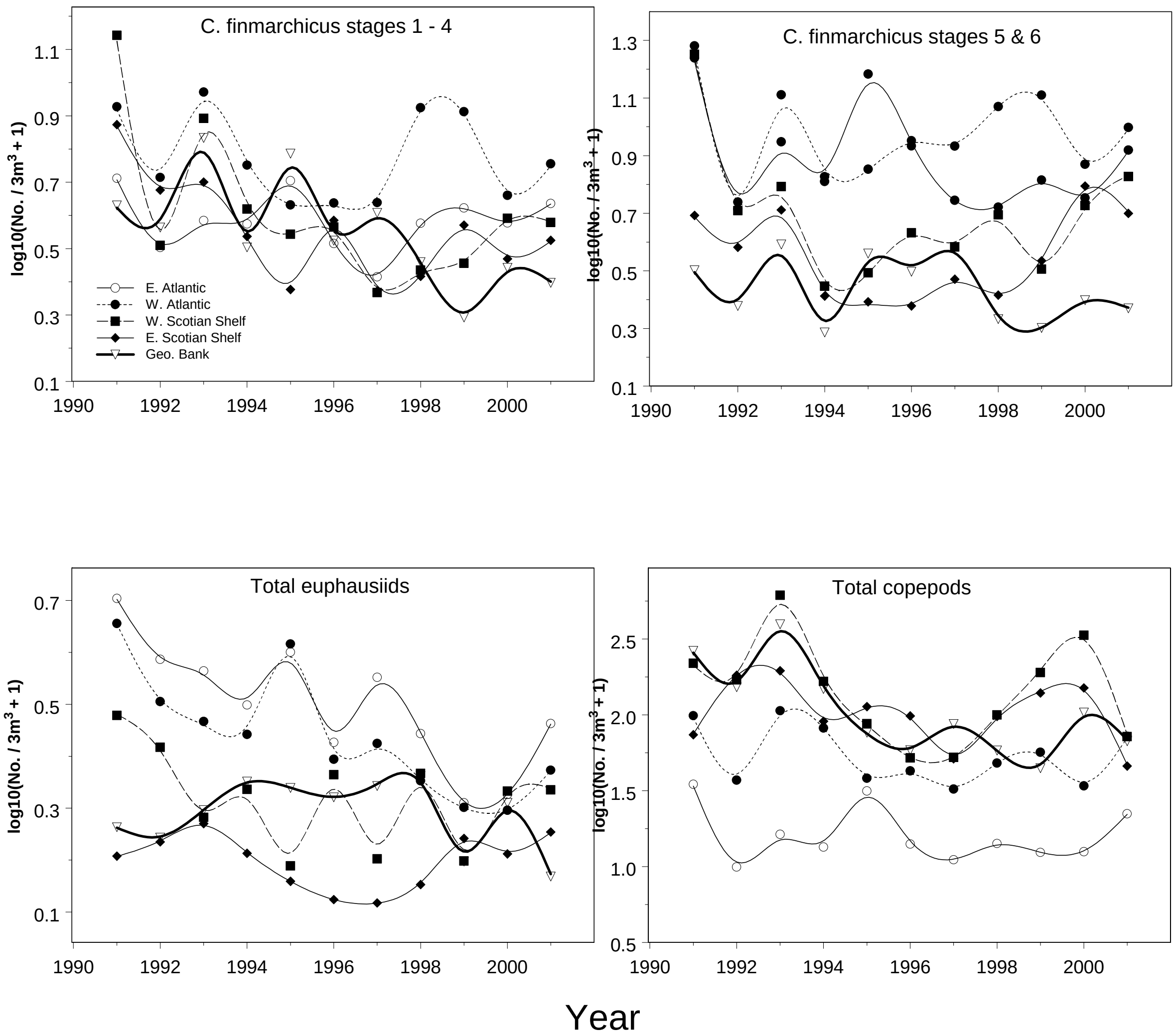


Fig. 4. Yearly means and spline smoothers for *C. finmarchicus* stages 1 - 4, *C. finmarchicus* stages 5 & 6total euphausiids and total copepods for the eastern Scotian shelf, western Scotian Georges Bank, western Atlantic and eastern Atlantic zones for years 1991 to 2001.

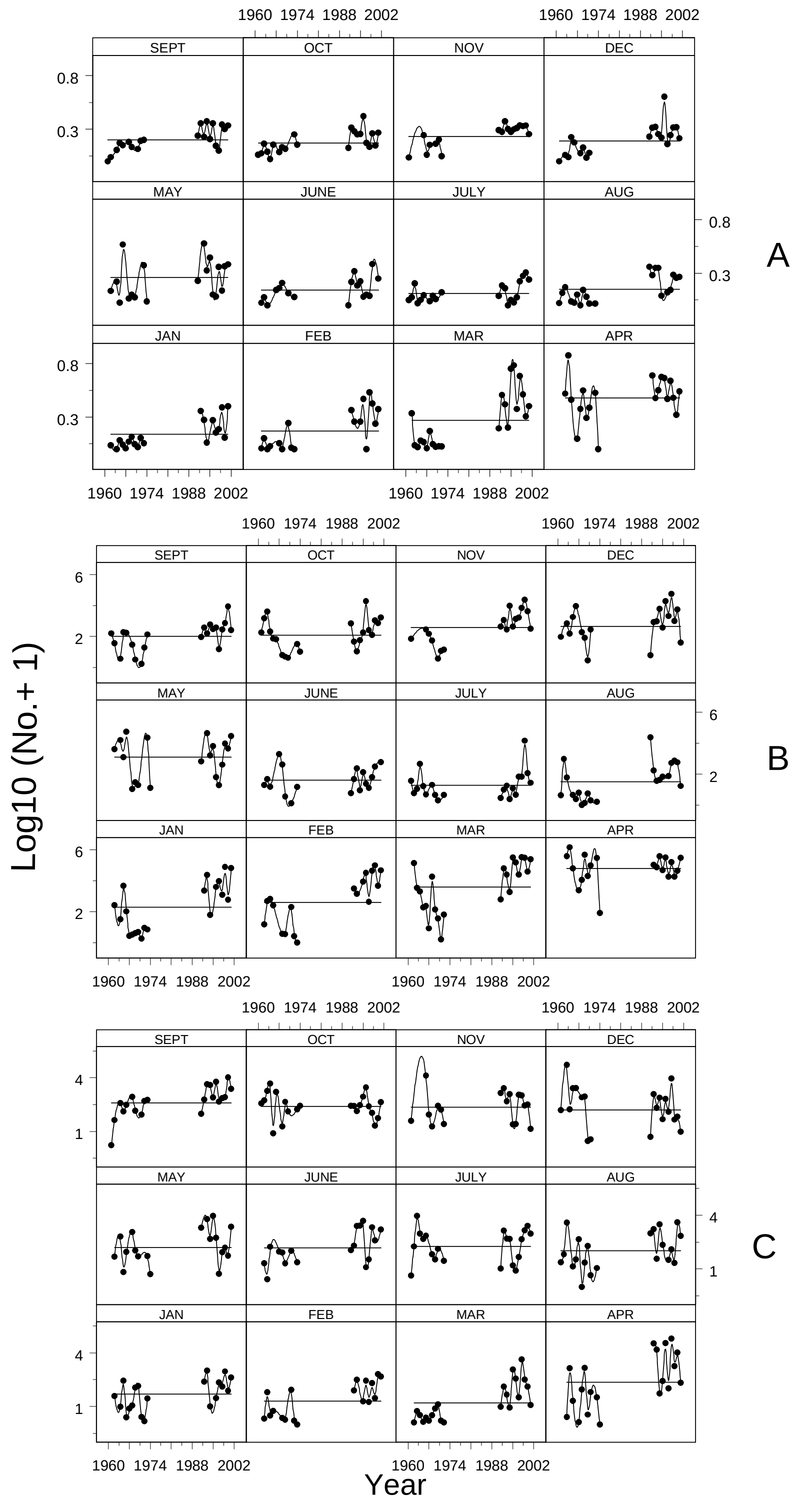
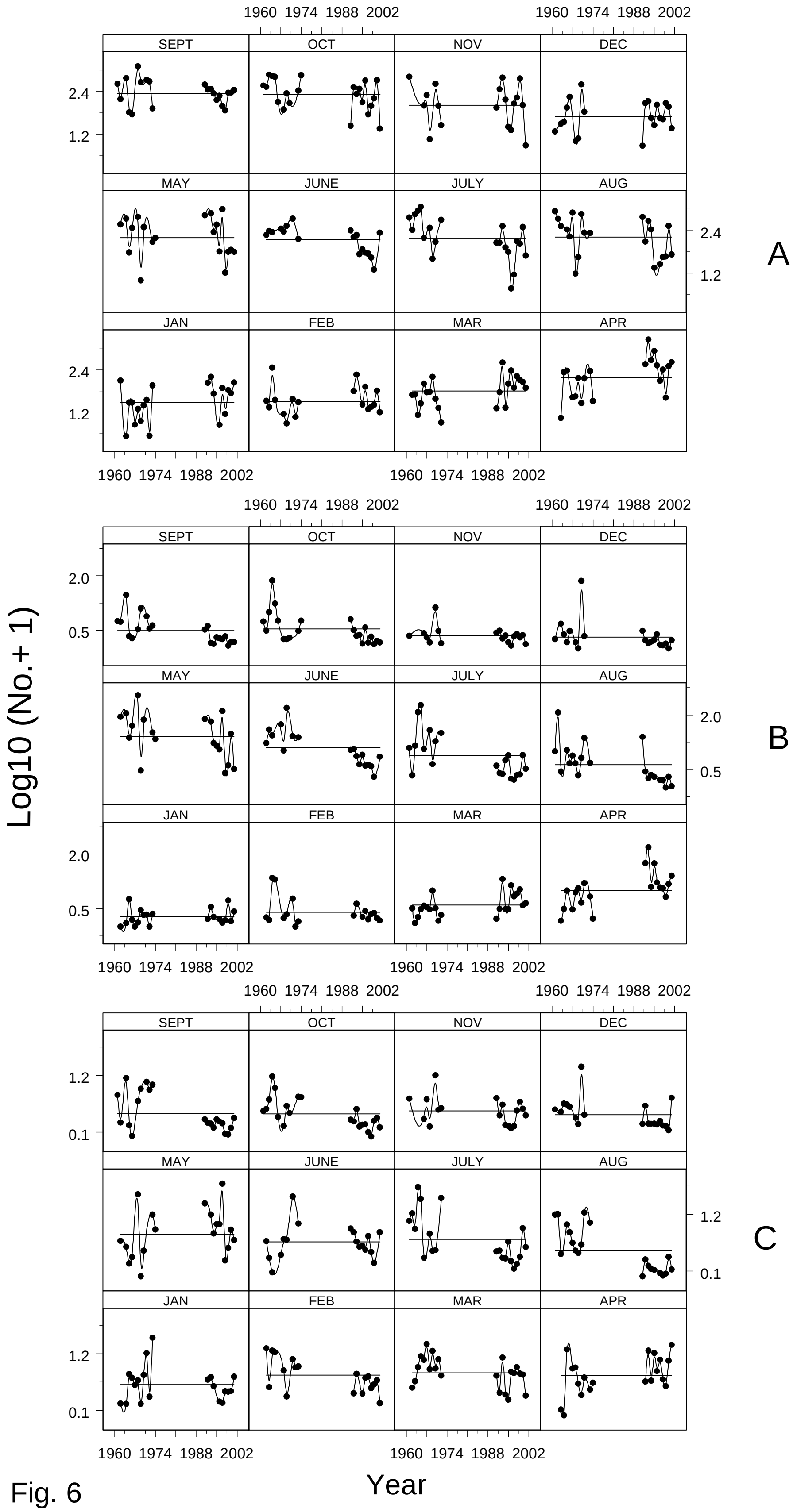


Fig. 5. Monthly means (dots) and spline smoother for each year plus the climatological means (horizontal lines) for each month for the taxa phytoplankton color index (A), total diatoms stages 1 - 4 (B), total dinoflagellates (C) for years 1961 to 2001 for eastern and western Scotian Shelf zones of the E line.


A
B
C
SEPT
OCT
NOV
DEC
MAY
JUNE
JULY
AUG
JAN
FEB
MAR
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1960 1974 1988 2002
2.4
1.2
2.0
0.5
0.1
Log10 (No.+ 1)
Year

Fig. 6

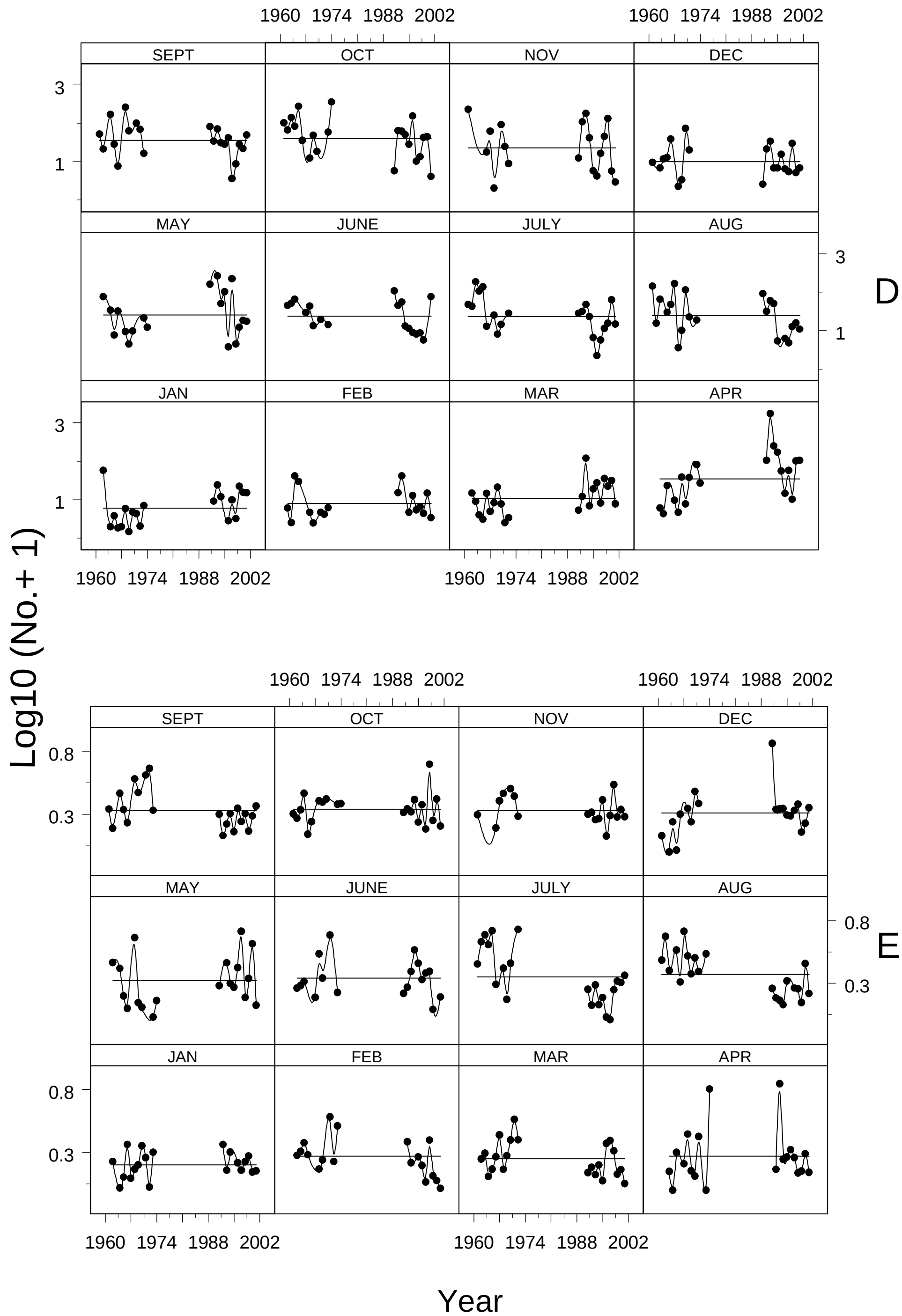

Fig. 6. Monthly means (dots) and spline smoother for each year plus the climatological means (horizontal lines) for each month for the taxa total copepods (A), *C. finmarchicus* stages 1 - 4 (B), *C. finmarchicus* stages 5&6 (C) *Pseudocalanus/ Paracalanus spp*. (D), and total euphausiids (E) for years 1961 to 2001 for eastern and western Scotian Shelf zones of the E line.

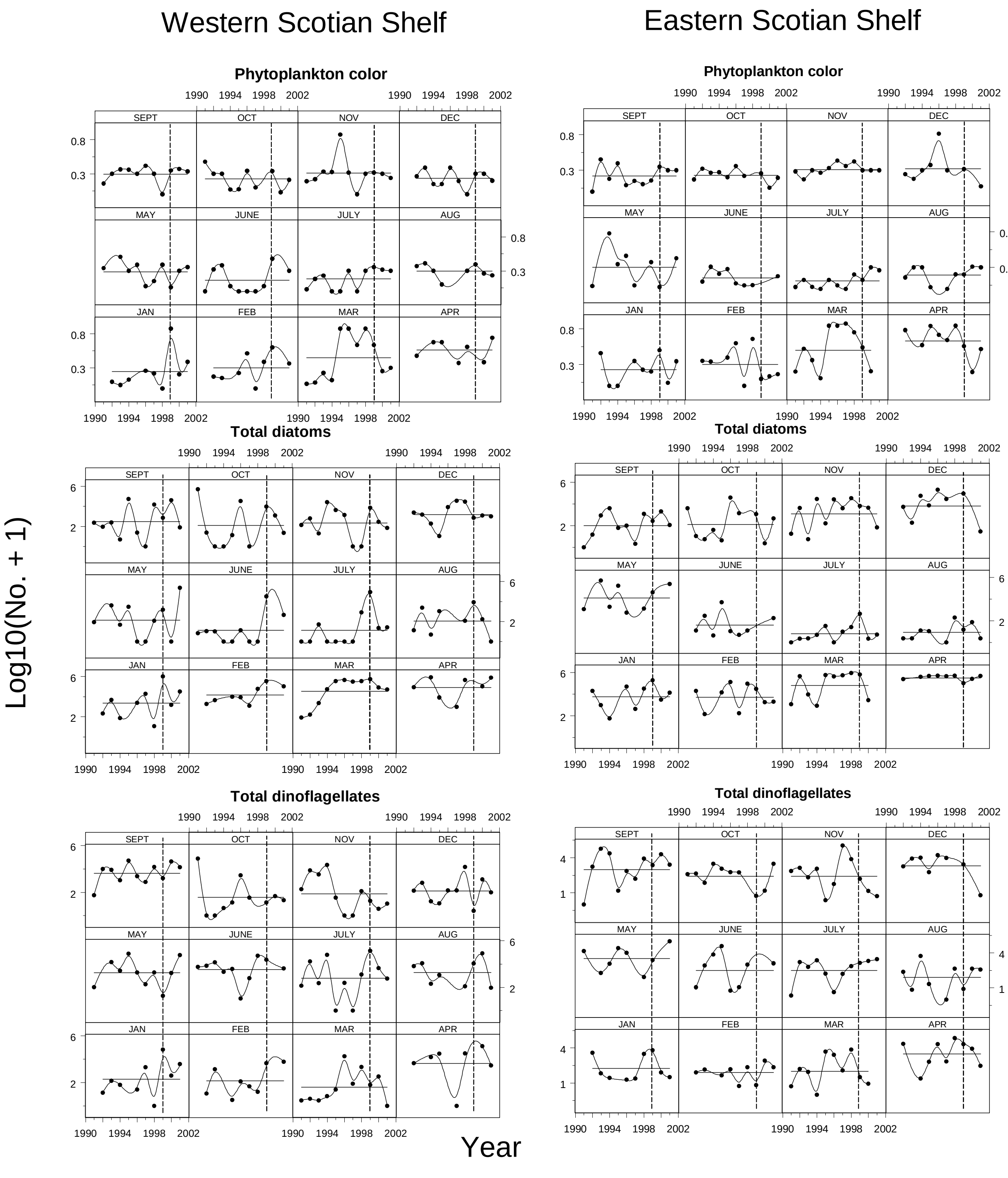

Fig. 7. Monthly means (dots), spline smoothers and monthly means (horizontal red line) for each year between 1991 and 2001 for the eastern and western Scotian Shelf E line. Horizontal dashed line shows position of 1999 data.

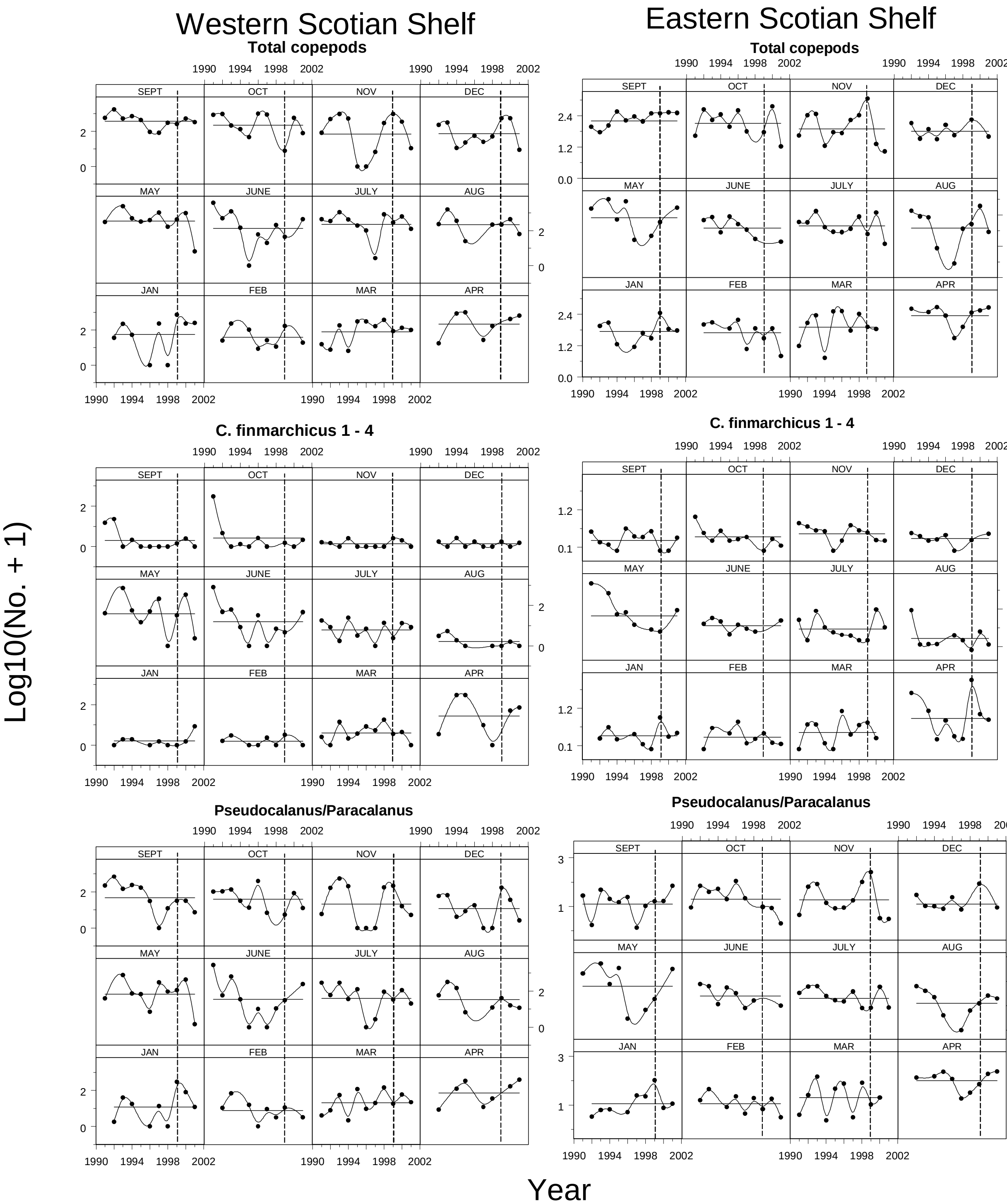

Fig. 8. Monthly means (dots), spline smoothers and monthly means (horizontal red line) for each year between 1991 and 2001 for the eastern and western Scotian Shelf E line. Horizontal dashed line shows position of 1999 data.

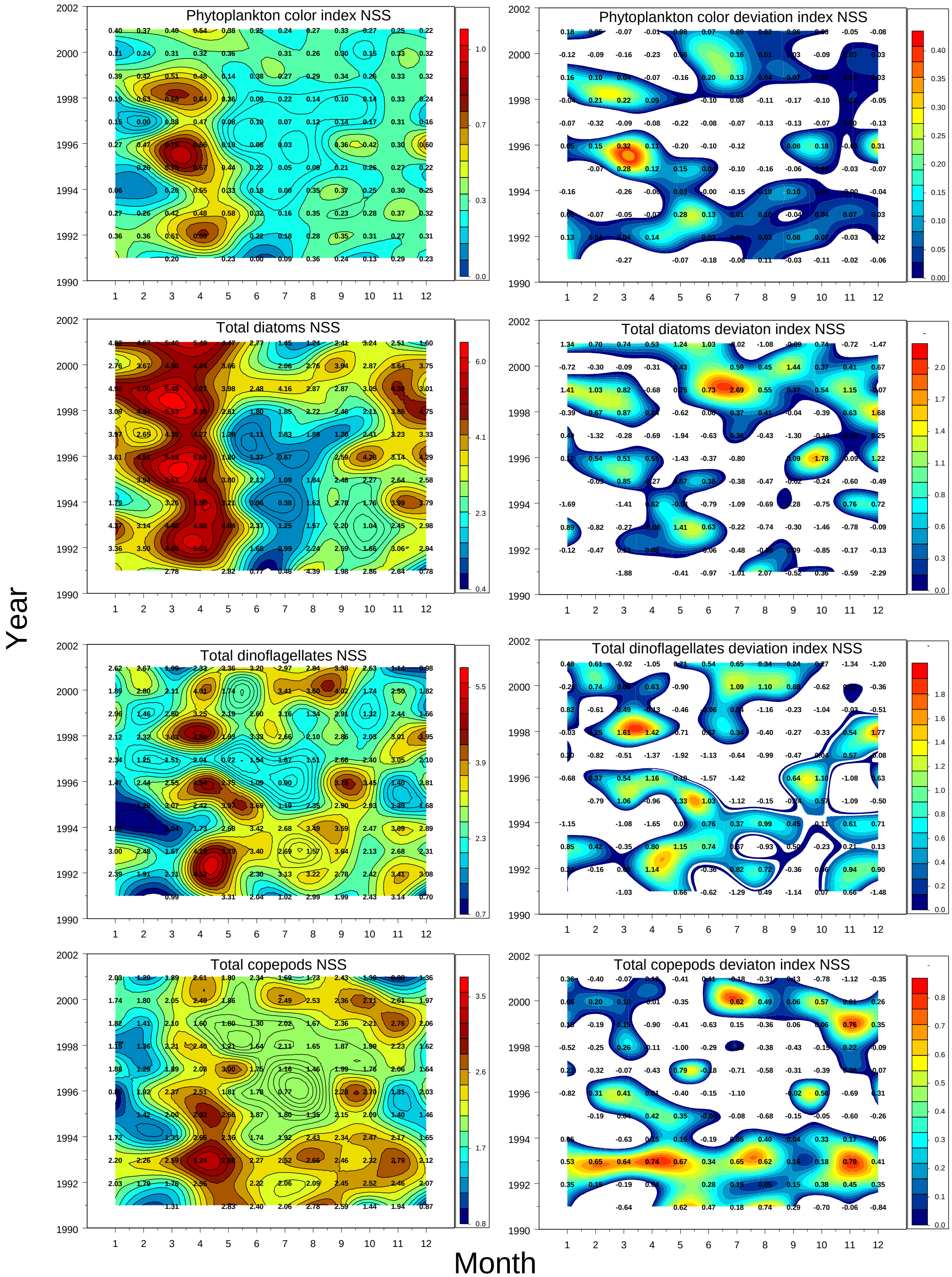

Fig. 9. Contours of monthly abundance and values for deviations from individual monthly means for the decade of 1991 to 2001 on the entire Scotian Shelf (zones B and C of the E line). Only contours above zero are shown the for deviation index.