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Assessing Phytoplankton and Zooplankton Taxa from the CPR Survey in NAFO Subareas 2 and 3 in the Northwest Atlantic.

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Abstract

Using data collected by the Continuous Plankton Recorder Survey, we review the spatial and temporal dynamics of selected phytoplankton and zooplankton assemblages in the Northwest Atlantic bounded by the NAFO Divisions 2HJ, 3K, 3M, 3LNO, and 3Ps (Subareas 2 and 3). Major shifts in the abundance, timing, and duration of some phytoplankton and zooplankton taxa enumerated as part of the CPR in the Northwest Atlantic have been observed. The potential impact of climatic variation on the abundance of the selected CPR taxa is evaluated at the annual and decadal time scales.

Introduction

The Continuous Plankton Recorder (CPR) Survey provides an assessment of long-term changes in abundance and geographic distribution of planktonic organisms ranging from small phytoplankton cells to larger macrozooplankton. (Warner and Hays, 1994). CPR collections in the northwest Atlantic began in 1959 and continued with some interruptions during the latter period through till 1986. Collections were renewed in 1991 and continue to present. The recorder is towed by ships of opportunity along a number of standard routes throughout the North Atlantic. The CPR device collects plankton at a nominal depth of 7 m, and organisms are retained on a moving band of silk material and preserved. Analyses are performed on sections of silk that represent 18.5 km tow distance and ca. 3m^3 of water filtered[1]. Every second section is analyzed providing a horizontal scale of ca. 37 km.

Throughout this report, we use the same level of identification of each taxonomic category obtained from the original microscopic analysis. The purpose of this report is to evaluate the long-term changes in plankton collected as part of the CPR program within the Northwest Atlantic bounded by the NAFO Divisions in Subareas 2 and 3. We focus on abundant organisms making up the base of the food chain (phytoplankton) as well as secondary producers and higher trophic levels supporting both prey and predators of larval and juvenile stages of fish and invertebrates, as well as adult stages of pelagic species.

Data and Methods

The data analyzed in this report extend from 1961 to 2002 with an intervening gap from 1979 to 1990. The sampling distribution was uneven for both spatial and temporal scales due to the nature of opportunistic sampling with ships of opportunity, variation in shipping routes, and CPR funding. The CPR taxa evaluated in this report included phytoplankton (Phytoplankton Colour Index, Diatoms and Dinoflagellates), the dominant microzooplankton taxon of copepod species and subspecies (*Calanus* sp., *Metrida* sp., *Oithona* sp. *Temora longicornis*, and copepod nauplii), important macrozooplankton (Euphausiacea, Hyperiidea, and *Euchaeta* sp.) and benthic meroplankton (Decapoda and Echinodermata). We mapped the spatial distribution of abundance of various CPR taxa by log-transforming ($\log_{10}(x + 1)$) abundance estimates, but we use the un-transformed counts and arithmetic means in the seasonal and

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

annual time series analysis within the different NAFO Divisions. We did not differentiate the data based on bathymetry (e.g. shelf versus slope) and included all the data bounded by the NAFO Divisions (data were pooled from NAFO Divisions to reduce the sampling bias into 2JH, 3K, 3LNO, 3M, and 3Ps). All data were standardized for each CPR taxon for the combined NAFO Divisions (Subareas 2 and 3) by estimating the monthly mean and standard deviation of the un-transformed abundance estimates for the series 1961-2002. Each average monthly observation was then standardized by subtracting the long-term monthly mean and dividing by the monthly standard deviation. We then computed annual anomalies by summing the monthly anomalies over then entire year (January-December). To evaluate interannual variability in the seasonal timing and abundance of these CPR taxa, we used kriging to produce contour maps from the irregular spaced monthly data. The potential impact of climatic variation on the abundance of the CPR taxa was examined. The ocean climate index, the North Atlantic Oscillation (NAO), describing the large-scale atmospheric circulation over the Atlantic, is the difference in winter (Dec.-Feb.) air pressures between the Azores and Iceland.

Results

CPR sampling in the NAFO Subareas 2 and 3 was uneven and limited during certain seasons and years and was confined to the main commercial shipping lanes (Fig. 1). The sampling effort of the CPR survey within the NAFO Subareas 2 and 3 varied from 19,491 observations during 1961-70, decreasing to 10,603 during 1970-86 and rising to 32,544 observations during 1991-02. Observations were unevenly collected from 1979 through to 1990 and were therefore excluded to reduce bias in our statistics.

Phytoplankton

The spatial maps of phytoplankton colour index indicated the widespread distribution of phytoplankton throughout the NAFO Divisions (Fig. 2a). The colour index was minimal during the 1970's and maximal during the 1990's, showing enhanced colour in the 3M, 3LNO, and 3Ps Divisions compared to the northerly regions (Fig. 2b). The seasonal distribution of the colour index showed peaks during spring, followed by a weaker fall bloom (Fig. 2c). The annual colour index varied from a low value of 1 during the early 1970's to values >3 periodically throughout the time series (Fig. 3a). The annual anomaly time series of phytoplankton colour was generally negative during the 1960's and early-1970's (Fig. 3b). Thereafter, the colour index increased during the mid-1970's and continued to show positive trends above the long-term mean into the early-mid 1990's, and since has shown a declining trend. Interannual variability in the strength and seasonal timing of phytoplankton blooms was evident during the time series. Phytoplankton blooms were observed to extend into the summer months during the 1960-70's, in contrast to the 1990's, where the main phytoplankton bloom occurs during spring (Fig. 3c).

One of the dominant phytoplankton taxa observed during the seasonal production cycle are Diatoms. A dominant Diatom genera in the Northwest Atlantic is *Chaetoceros* sp., which have a widespread distribution throughout the Northwest Atlantic (Fig. 4a). The seasonal occurrence of this genus shows peaks during spring through early summer, and again during the fall (Fig. 4b). The average abundance was slightly greater in NAFO Divisions 3LNO and 3Ps during the 1990's compared to the northerly Divisions in previous decades (Fig. 4c). The mean annual abundance estimates varied from $1x10^4$ cells m^{-3} to concentrations > $3x10^4$ cells m^{-3} (Fig. 5a). The annual anomaly time series indicated slightly below average Diatom cell densities throughout the 1961-2002 series (Fig. 5b). Above average Diatom blooms were observed in 1962, 1974-75, 1991-92, and 2001-02. The seasonal occurrence of *Chaetoceros sp.* indicated a shift to earlier and shorter blooms during the 1960-1970's, although the timing of the fall blooms remained largely unchanged (Fig. 5c).

Another common phytoplankton represented in the CPR are dinoflagellates of the genus *Ceratium*. This genus also shows a widespread distribution on the shelf and slope waters within the NAFO Divisions (Fig. 6a). The seasonal occurrence and mean abundance of this species is similar to that of *Chaetoceros* sp. showing both early spring and fall blooms, and enhanced concentrations in 3LNO and 3Ps during the 1990's (Fig. 6bc). The annual abundance and anomaly time series showed consistent below average concentrations throughout the 1960-70's, followed by an abrupt increase in mean abundance during the mid-90's and declining thereafter to near the long-term mean (Fig. 7ab). This genus was also more prevalent throughout the year in the 1990's in contrast to the period 1961-78, when its abundance was restricted more to the periods associated with the spring and fall blooms (Fig. 7c).

Zooplankton – Copepods

The calanoid and cyclopoid copepods make up a significant proportion of the total microzooplankton assemblage in the Northwest Atlantic (Pepin *et al*., 2003). The species *Calanus finmarchicus* is very common throughout the North Atlantic and represents an important linkage from primary producers to higher trophic levels. This species is widely distributed throughout the NW Atlantic and shows a repeatable N-S gradient in the NAFO Divisions (Fig. 8ab). Peak abundance occurs during the late spring and summer months (Fig. 8c). The mean annual abundance of *C. finmarchicus* varied from 5 m^{-3} to levels in excess of 40 m^{-3} (Fig. 9a). The annual anomaly time series for this species was near the long-term mean during the 1960's and early-1970's, and showed above average densities during the mid-1970's (Fig. 9b). In general, the abundance of *C. finmarchicus* was slightly below the long-term mean throughout the 1990's. A shift in the seasonal timing and abundance occurred during the 1960-70's and early-1990's as this species appeared progressively later during the season, and returned to the average climatology during the latter part of the time series (Figure 9c).

Another important calanoid in the NW Atlantic is *Calanus hyperboreus*. The distribution of this species is mainly confined to the outer shelf and slope waters and has increased in abundance during the last two decades in NAFO Div. 3K, 3LNO, and 3M (Fig. 10ab). Although the average abundance of this species is low, ranging from <10 m^{-3}, its body size is approximately 10 times greater than that of *C. finmarchicus*, and thus contributes significantly to the overall biomass of copepods in the NW Atlantic. *C. hyperboreus* is most abundant during the months of April – June (Fig. 10c). The mean annual abundance of this species has progressively increased during 1961-2002 (Fig. 11a). The annual anomaly time series for *C. hyperboreus* was negative during the 1960's and early-1970's, followed by above average densities during the mid-1970's, early- and late-1990's (Fig. 11b). The seasonal timing of *C. hyperboreus* has varied little during the period 1961-2002 (Fig. 11c).

Another common and abundant copepod genera is *Paracalanus-Pseudocalanus* sp. (these genera are grouped together due to their structural similarities) and show a widespread distribution with higher concentrations observed on the southern shelf relative to the offshore or northerly waters (Fig. 12ab). These genera remain abundant throughout the year on the Newfoundland Shelf (Fig. 12c). A peak in mean abundance was observed at the start of the series in 1961, followed by an abrupt reduction in density and a gradual negative trend in abundance through the 1960's and 1970's (Fig. 13ab). Initial peaks in abundance observed in the early and late-1990's, were followed by declining trends in abundance through the mid-1990's (Fig. 13b). A shift in the seasonal timing and abundance occurred after 1991 as *Paracalanus-Pseudocalanus* sp. appeared earlier and were less abundant during the late spring-summer months in contrast to 1961-78 (Fig. 13c).

In contrast to the widely distributed *Calanus* genera, the copepod *Temora longicornis* is only observed in the coastal and inner Newfoundland Shelf and is not found in the northerly NAFO Divisions (Fig. 14ab). The decadal mean abundance has declined somewhat during the time series. The seasonal climatology indicates peak abundance occurs during the summer-fall months (Fig. 14c). The annual mean abundance was very similar to that of *Paracalanus-Pseudocalanus sp.*, showing a peak in 1961, relatively stable levels throughout the 1960's, and declining abundance through the 1970's and 1990's, along with a substantial negative anomaly during the mid- to late-1970's (Fig. 15ab). The seasonal timing of *T. longicornis* has varied little during the period 1961-2002 (Fig. 15c).

The cyclopoid copepod *Oithona* sp. is widely distributed on the Newfoundland Shelf and has increased in abundance in the southern NAFO Divisions during the 1990's (Fig. 16ab). This copepod species remains abundant throughout much of the year on the Newfoundland Shelf (Fig. 16c). The abundance of this genus declined through the 1960's and early-1970's, followed by a peak in 1974, and then during the early- to mid-1990's with levels above the long-term mean before showing a gradual negative trend into the late-1990's (Fig. 17ab). A shift in the seasonal timing and abundance occurred after 1991 as *Oithona* sp. appeared earlier and were more abundant during the early spring and late fall periods in contrast to 1961-78 (Fig. 17c).

The distribution of the copepod *Metrida* sp. tends to be associated with slope water (1000 m isobath) regions on the NE Newfoundland Shelf and Grand Banks with lower densities on the Shelf, and no latitudinal gradient apparent among the NAFO Subareas (Fig. 18ab). The seasonal climatology indicated relatively low concentrations throughout the year, with somewhat higher values observed during the spring-summer months (Fig. 18c). The trends in annual mean abundance were mainly below the long-term average through the 1960's and 1970's with the exception of a positive anomaly in 1967 (Fig. 19b). An overall negative trend in the annual anomaly time series was observed during the later part of the series. A shift in the seasonal timing to earlier periods similar to that of the copepod taxa examined above was evident for *Metrida* sp. (Fig. 19c).

The naupliar stages of copepods represent important prey sources for the larval stages of fish and invertebrates. The distribution of copepod nauplii is widespread over the shelf slope, and offshore waters and mean abundance has increased systematically during the last 3 decades (Fig. 20ab). The seasonal climatology indicates that nauplii are present throughout the year (Fig. 20c). The annual mean abundance of copepod nauplii remained below the long-term average through the 1960's and early-1970's, followed by above average densities in the mid-1970's (Fig. 21ab). The overall trend for the 1990's was above the long-term mean. The shift to earlier timing of occurrence that was observed in adult copepods noted above, was also observed in this early developmental stage during the 1960’s and 1970’s (Fig. 21c).

Macrozooplankton

The distribution of Euphausiacea was similar to that of *Metrida* sp. with higher densities confined to the slope water and offshore regions, along with higher abundance in the northerly NAFO Divisions compared to the southern areas (Fig. 22ab). The seasonal climatology indicated peak abundance occurred during the summer months (Fig. 22c). The annual mean abundance levels were above the long-term mean during the early-mid 1960's, followed by a overall declining trend through the 1970's (Fig. 23ab). The early-1990's were characterized by above average densities, compared to the mid and late-1990's which showed negative trends in mean annual abundance. The enhanced densities of Euphausiacea observed during the 1961-2002 period were generally confined to the late spring-summer months (Fig. 23c).

The spatial distribution of Hyperiidea was limited on the Newfoundland Shelf, with higher densities observed in the Slope waters and offshore, along a N-S latitudinal gradient in the NAFO Divisions (Fig. 24ab). The seasonal climatology indicated peak abundance during the late spring-summer months (Fig. 24c). The annual mean abundance was relatively stable and near the long-term mean throughout the time series, with the exception of 1961 which showed a moderate negative anomaly (Fig. 25ab). Higher densities of Hyperiidae were observed throughout the spring-summer months, somewhat delayed in the late-1970's and slightly earlier in the mid- to late-1990's (Fig. 25c).

The spatial distribution of *Eucheata* sp. was similar to that of the Hyperiidea being restricted to the slope waters and offshore areas (Fig. 26a). The abundance of *Eucheata* sp. was relatively low throughout the NAFO Divisions with densities <4 m^{-3} (Fig. 26b). The seasonal climatology indicated peak abundance during the late spring-summer months (Fig. 26c). The annual mean abundance was below the long-term average during the early-1960's, followed by above average concentrations through the mid-1970's, and then declining again through the late-1970's and 1990's (Fig. 27ab). The seasonal timing and abundance of *Euchaeata* sp. indicated a slight shift to earlier appearance through the 1960-70's, but remained relatively consistent during the 1990's with timing and peak levels during the summer months (Fig. 27c).

Meroplankton

The meroplankton are transient residents of the plankton and generally only reside in the water column during the early life stages, and thereafter migrate or settle to benthic habitats. The Decapoda enumerated by the CPR Survey included the larval stage only. The distribution of this taxa was relatively sparse throughout the NAFO Divisions, increasing slightly in the southerly direction, and were mainly concentrated on the northeast and southern Newfoundland Shelf (Fig. 28ab). This taxa is most abundant during the late spring-summer months (Fig. 28c). The annual mean abundance was normally below the long-term mean for much of the 1961-77 series, with a large peak observed in 1975 (Fig. 29ab). The mean abundance during the 1990's was generally near the long-term mean. The seasonal timing and abundance of decapod larvae indicated a shift to earlier appearance through the 1990's relative to the 1960's and 1970's (Fig. 29c).

Another abundant meroplankton, the Echinodermata, were also mainly concentrated on the northeast and southern Newfoundland Shelf, and showed a similar increase in abundance in the southern NAFO Divisions (Fig. 30a). The mean abundance levels in the NAFO Divisions were enhanced in 3M during the 1970's, while 3Ps showed elevated concentrations during the 1960's and 1990's, respectively (Fig. 30b). The seasonal climatology indicated multiple peaks in abundance during the year, likely related to different life history strategies of the various species contained within this phylum (Fig. 30c). The annual mean abundance values ranged from <20 m^{-3} to over 160 m^{-3} during the series (Fig. 31a). The annual anomaly time series showed below average values through the 1960's and 1970's and 1990's with a large positive anomaly in 1993 (Fig. 31ab). The seasonal timing and abundance of the Echinodermata revealed significant changes in the appearance; spring and fall blooms dominating through the early-1960's, shifting to spring and summer blooms during the early- to mid-1970's, and summer-fall blooms during the early- to mid-1990's (Fig. 31c).

Influence of Climatic Variation

We evaluated the relationship between the NAO index and the annual abundance anomalies for the different CPR taxa to evaluate the potential for changes in ocean climate conditions on the biological dynamics. Previous studies have established relationships between climatic indices and ocean temperature on marine resources (Fig. 32). We did observe that certain CPR taxa were weakly correlated with the NAO Index, although other taxa showed no clear relationships (Fig. 33). Most of the relationships showed weak correlations, and indicated that positive NAO indices were related to higher abundance levels, with the exception of *T longicornis*, where the reverse was true. The expectation is that during negative phases of the NAO, warmer ocean climate conditions will prevail with weakening of the general northwesterly atmospheric flow, reduced convective mixing resulting in warmer air temperatures, reduced sea ice extent and warmer-saltier ocean conditions. During positive phase of the NAO, intensification of the NW flow resulting in increased convective mixing and sea ice extent, and colder-fresher ocean conditions. The possible mechanisms for increased secondary production under positive NAO indices include greater convective mixing resulting in reduced stratification leading to greater nutrient fluxes and primary productivity supporting higher secondary production. In the case of the reversed trend observed in *T longicornis*, this species is usually associated with warmer water masses, and would likely be displaced under cooler water masses characteristic of positive NAO indices (Pepin *et al.*, 2003).

Summary

- The CPR Survey represents the longest spatial and temporal time series of phytoplankton and zooplankton taxa in the northwestern Atlantic and on the Canadian eastern continental shelf.
- There have been major changes in the abundance, timing, and duration of major phytoplankton and zooplankton taxa in the NAFO Divisions in Subareas 2 and 3.
- During the recent decade, most of the phytoplankton production is concentrated during the spring bloom, in contrast to the 1960-70's, where blooms were observed during the summer and fall months.
- Evidence of earlier spring diatom blooms through the 1960-70's and the proliferation of dinoflagellates in the 1990's was noted.
- Over the period of the 1960-70's, delays in the seasonal occurrence of *Calanus finmarchicus* were observed, while during the 1990's we noted a general reduction in abundance of this copepod.
- A marked reduction in the abundance of *Temora longicornis* (warm water species) coincided with a general reduction in ocean temperatures in the early-1970's and 1990's.
- A consistent increase in the overall abundance of *Calanus hyperboreus* and copepod nauplii were noted in the NAFO Subareas 2 and 3 during the past three decades.
- A shift in the seasonal timing of occurrence to earlier periods was noted for several taxa; *Paracalanus-Pseudocalanus* sp., *Temora longicornis*, *Oithona* sp., *Metrida* sp., *Hyperiidae*, *Euchaeata* sp., and Decapoda.
- Higher abundance and positive annual anomalies characterized the early-1990's in several CPR taxa including both phytoplankton and zooplankton; the phytoplankton colour index, diatom, *Paracalanus-Pseudocalanus* sp., *Oithona* sp., *Metrida* sp., Decapoda, Hyperiidae, Euphausiacea, and Echinodermata.
- An index representing the strength of the atmospheric circulation in the Northwest Atlantic (NAO) inducing changes in ocean climate and sea ice extent, and annual temperature anomalies, was weakly correlated in some cases with the annual anomalies in abundance of the different CPR taxa examined.

Acknowledgements

We thank Mary Kennedy at the Bedford Institute of Oceanography in Dartmouth, NS, for her expertise in extracting the CPR data from the NAFO Divisions in Subareas 2 and 3 on our behalf. We are grateful for the efforts of Eugene Colbourne for the provision of the NAO Index information and the staff at the Northwest Atlantic Fisheries Centre

Biological and Physcial Oceanography Section for their acquisition, quality control and archiving of the hydrographic data.

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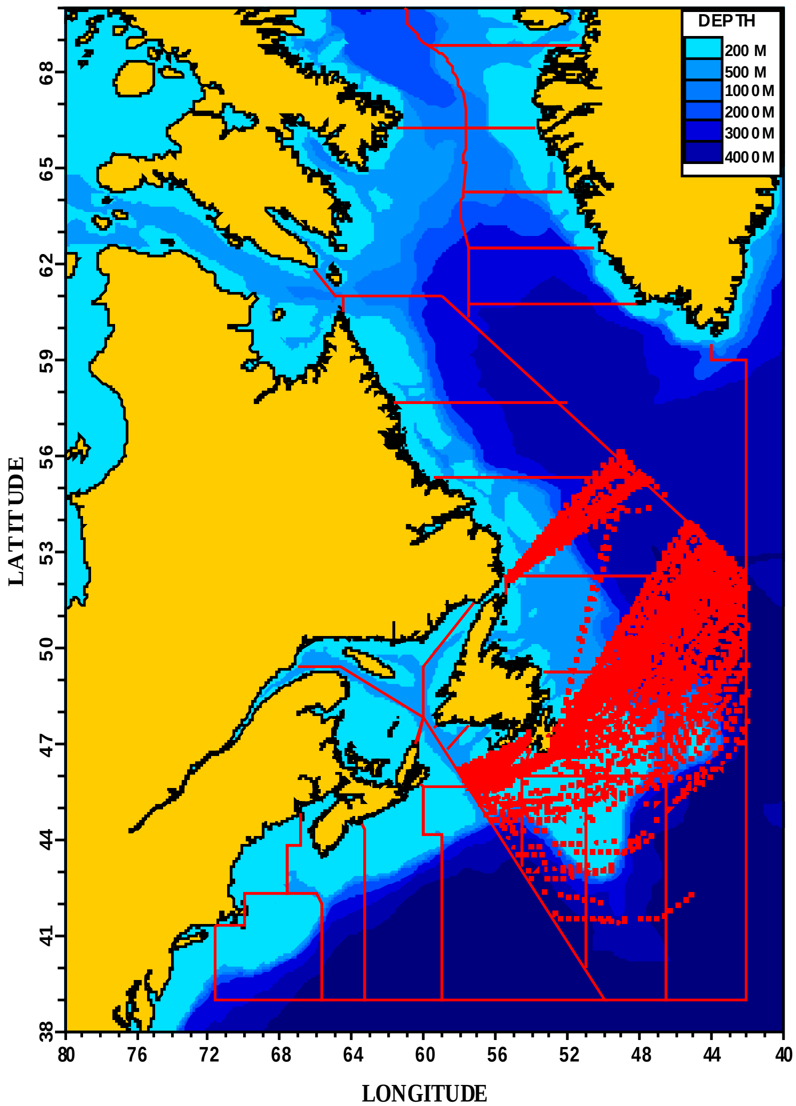

Fig. 1. Overlay of CPR stations in the Northwest Atlantic from 1961 to 2002. Each dot represents the centre of a 18.5 km tow section in NAFO Subareas 2 and 3. Note the concentrated sampling along standard CPR routes.

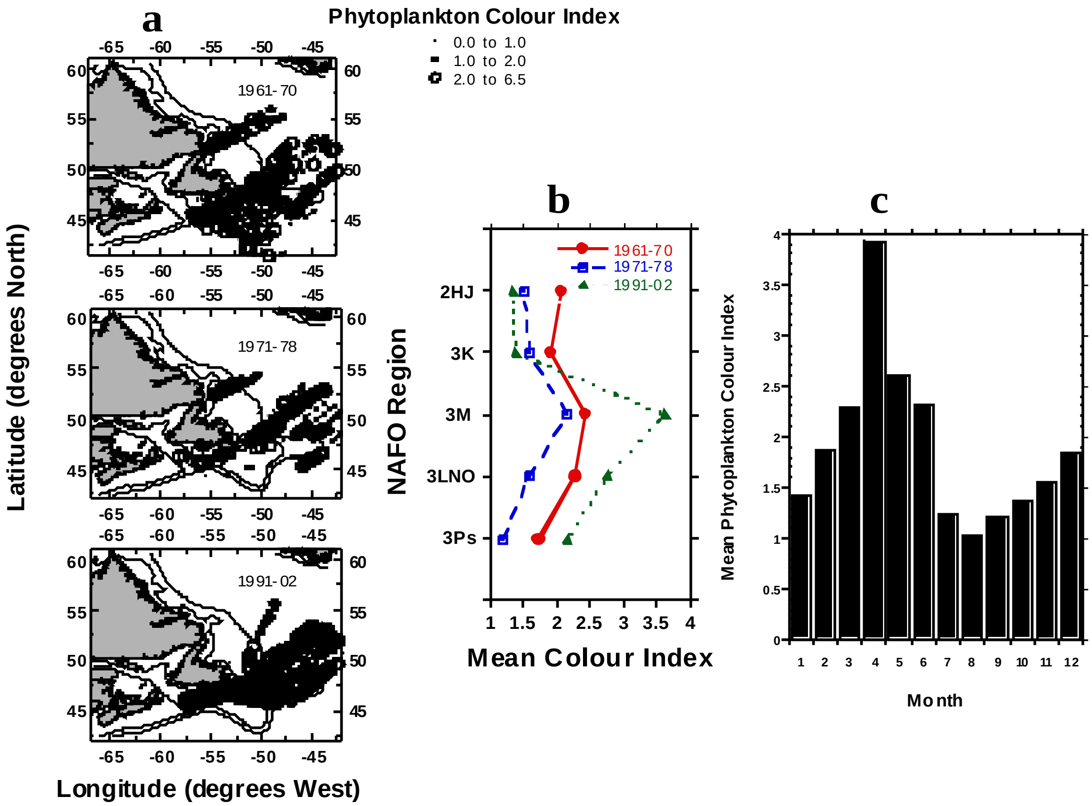

Fig. 2. (a) Spatial maps of abundance (area of circle proportional to observed count) for the phytoplankton colour index during three periods; 1961-70, 1971-78, and 1991-2002, (b) Annual means in abundance of the colour index by NAFO Divion, (c) Seasonal climatology in timing of occurrence of the phytoplankton colour index (all NAFO Divisions pooled).

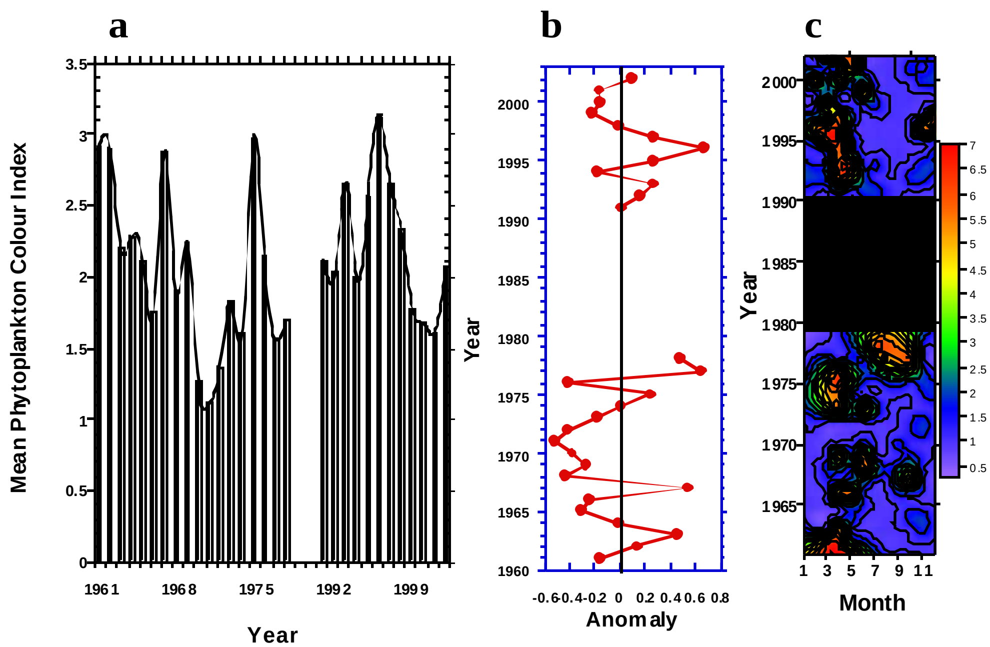

Fig. 3. (a) Annual time series of mean phytoplankton colour index (note sample gap between ca. 1979-1990), (b) annual phytoplankton colour index anomaly (standardized by standard deviation), (c) Contour plot of monthly mean abundance of phytoplankton colour index *versus* year.

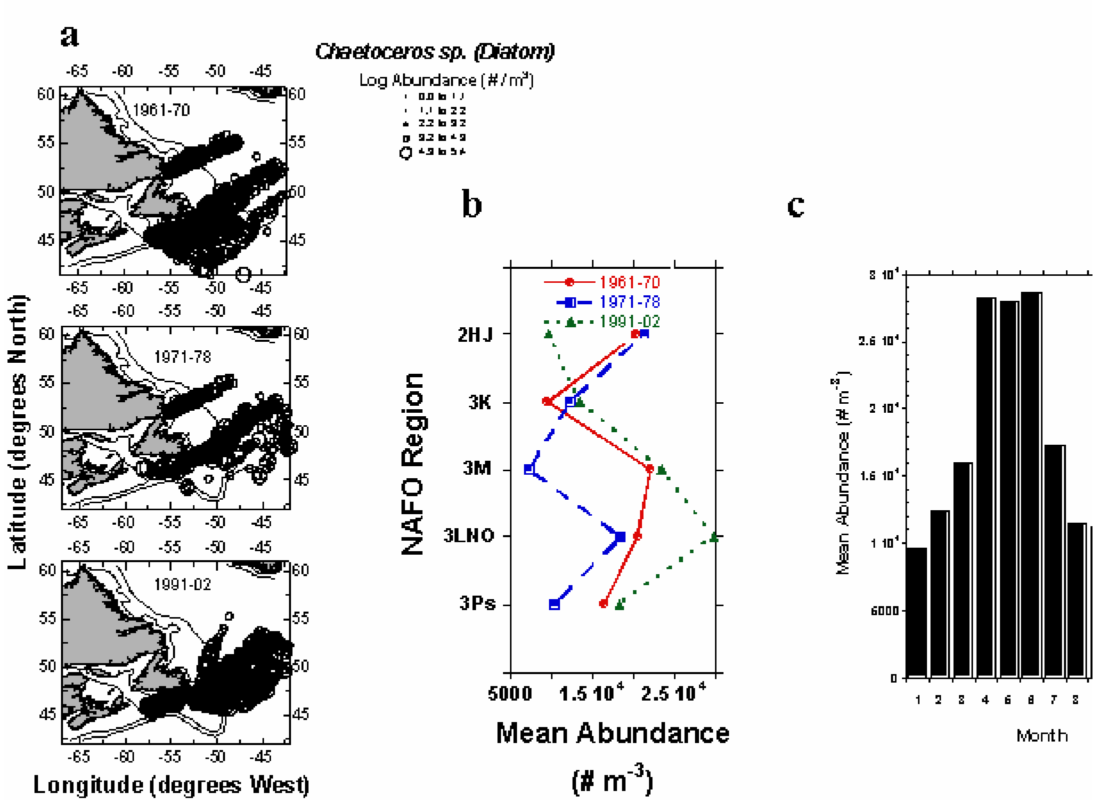

Fig. 4. Data presentation as in Figure 2 for the Diatom – *Chaetoceros* sp.

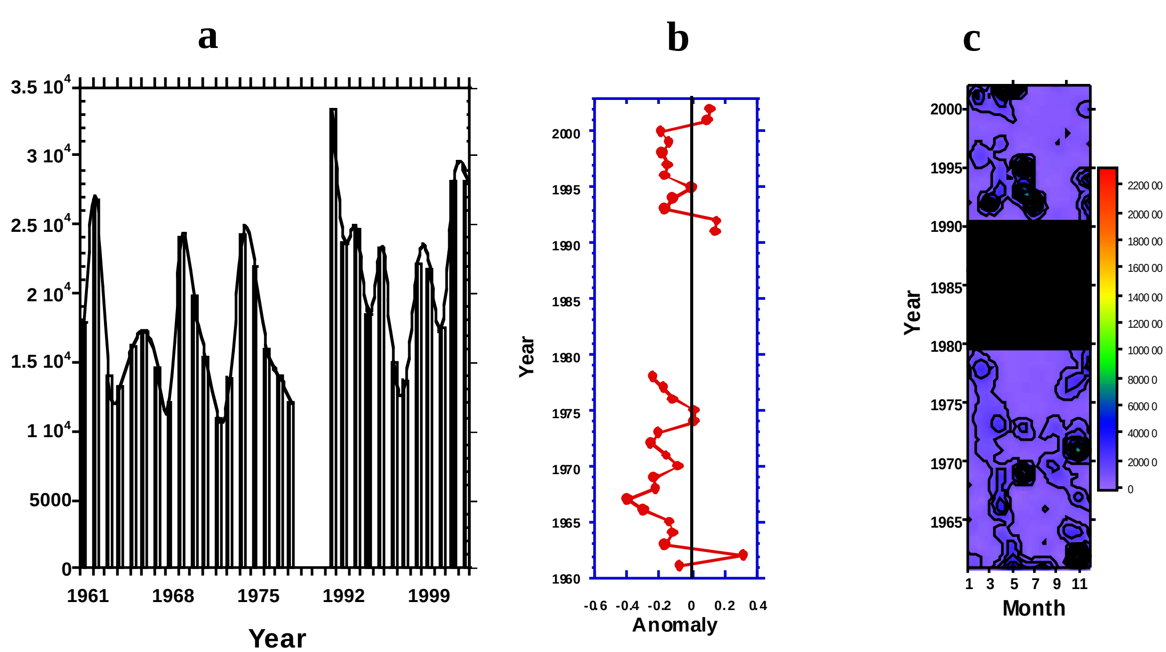

Fig. 5. Data presentation as in Figure 3 for the Diatom – *Chaetoceros* sp.

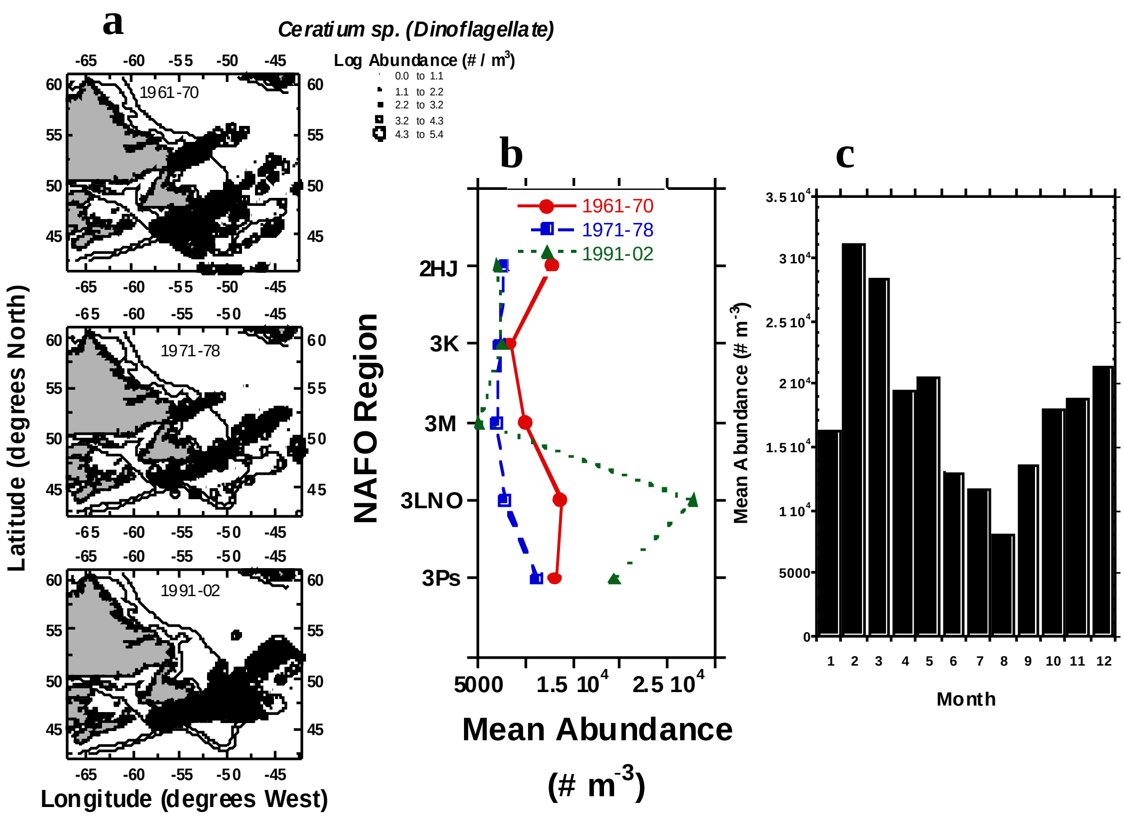

Fig. 6. Data presentation as in Figure 2 for the Dinoflagellate – *Ceratium* sp.

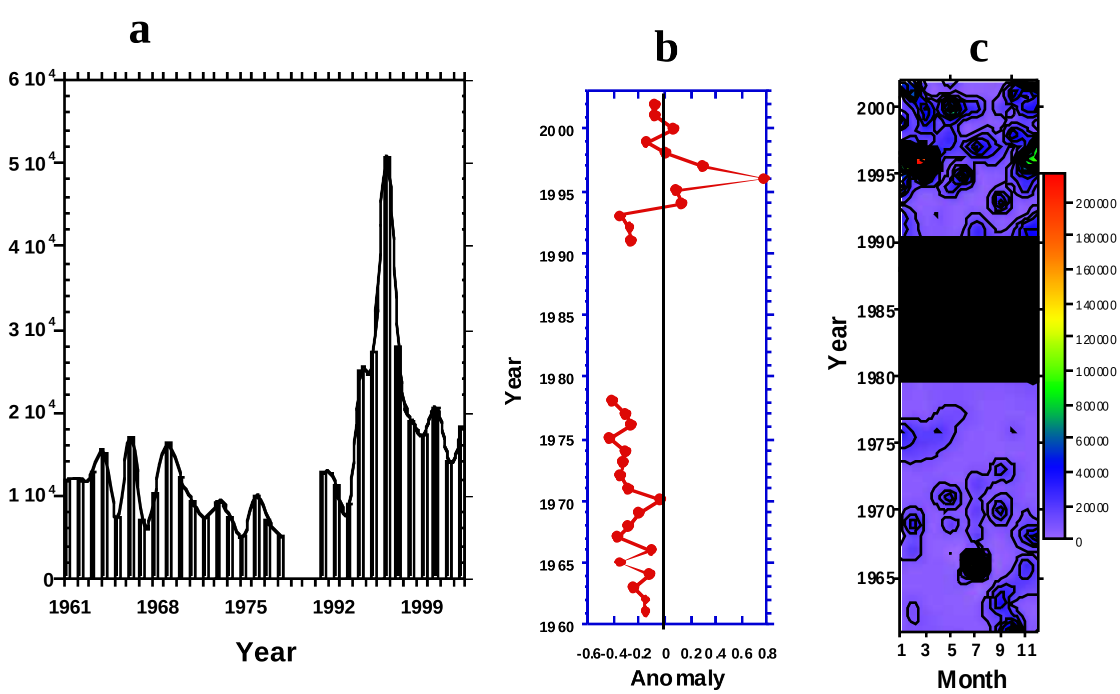

Fig. 7. Data presentation as in Figure 3 for the Dinoflagellate – *Ceratium* sp.

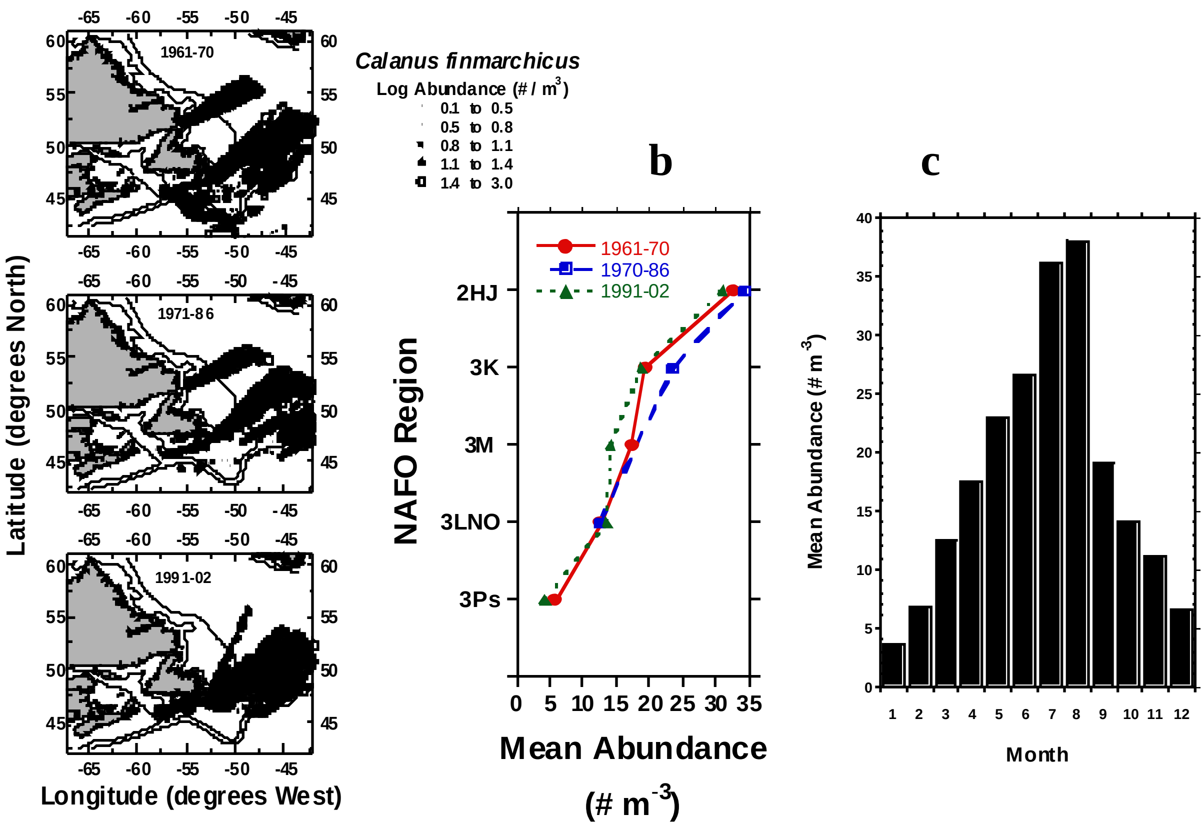

Fig. 8. Data presentation as in Figure 2 for *Calanus finmarchicus*.

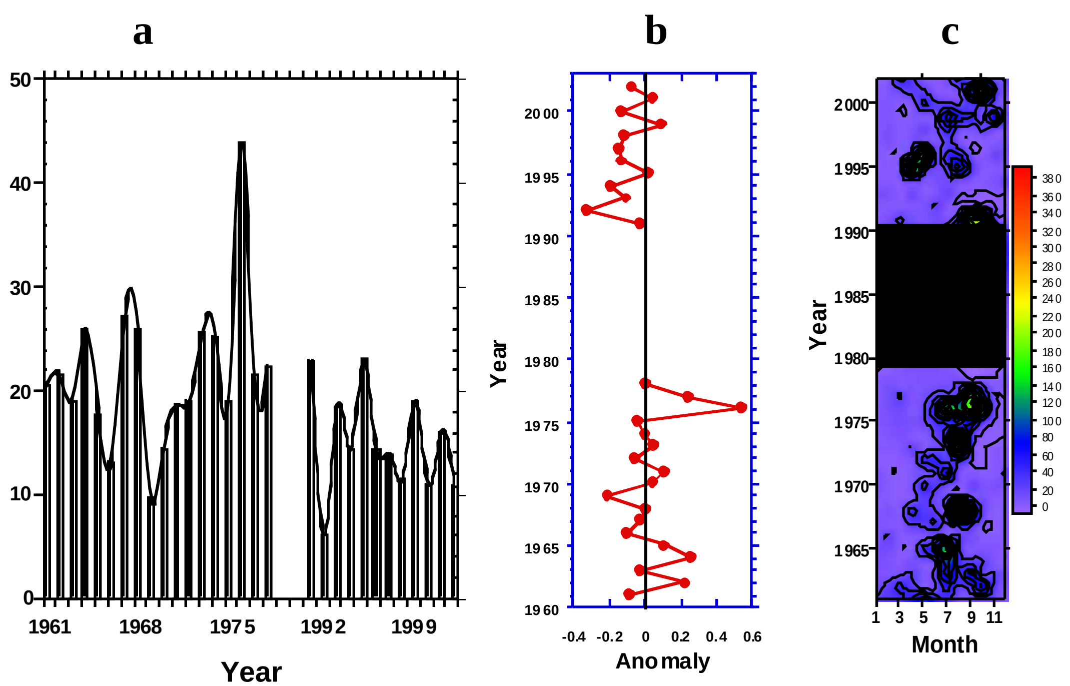

Fig. 9. Data presentation as in Figure 3 for *Calanus finmarchicus*.

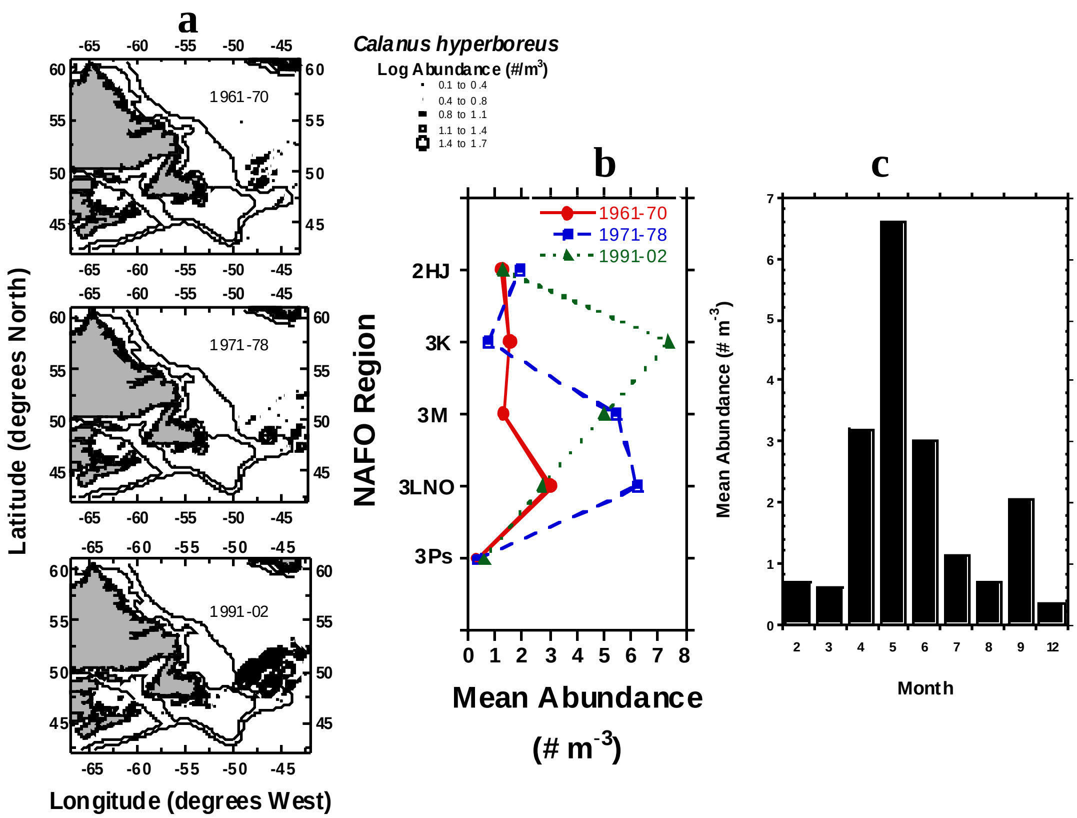

Fig. 10. Data presentation as in Figure 2 for *Calanus hyperboreus*.

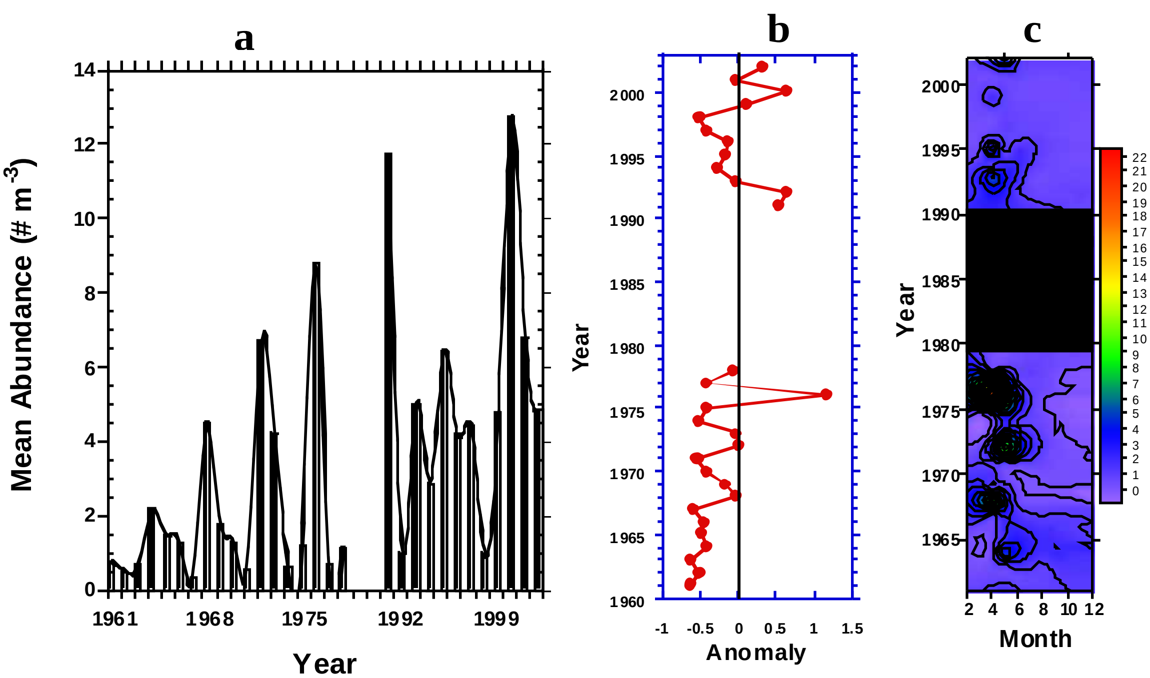

Fig. 11. Data presentation as in Figure 3 for *Calanus hyperboreus*.

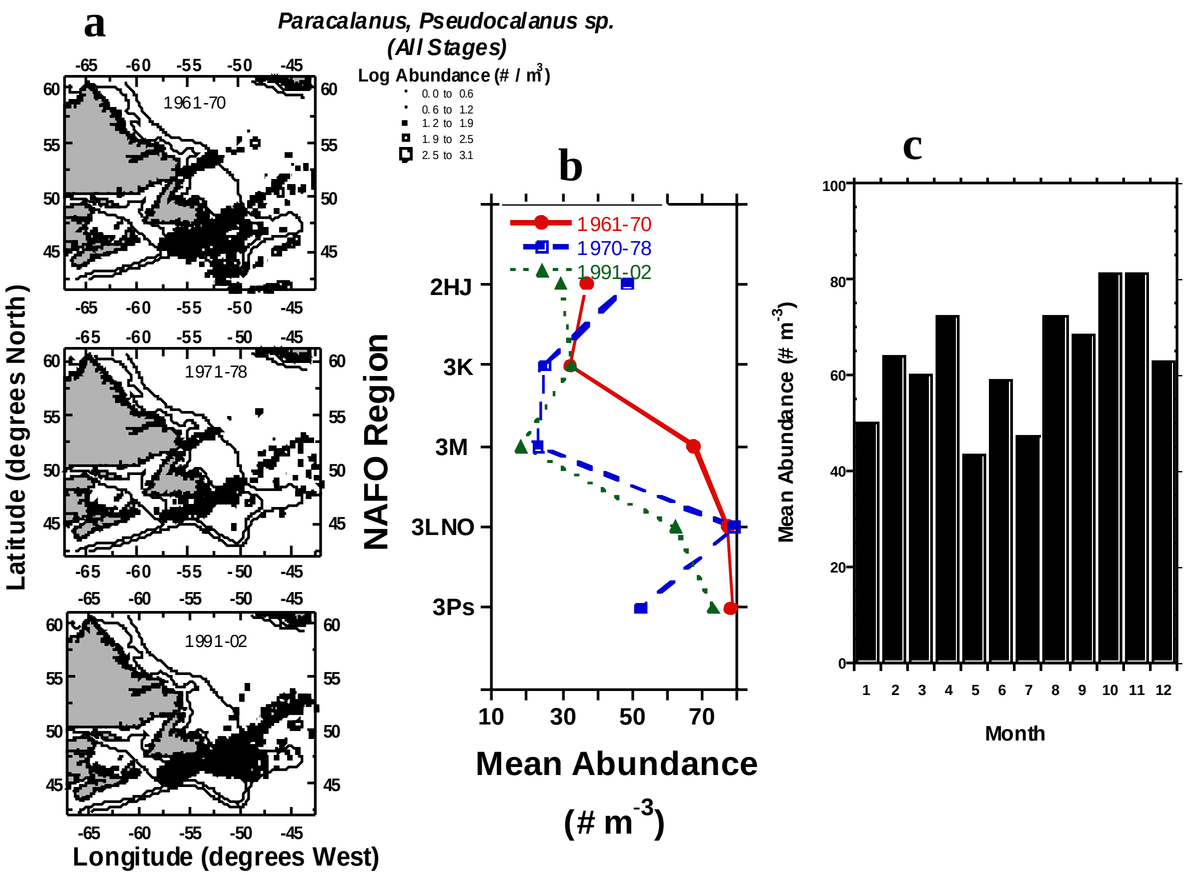

Fig. 12. Data presentation as in Figure 2 for *Paracalanus-Pseudocalanus* sp.

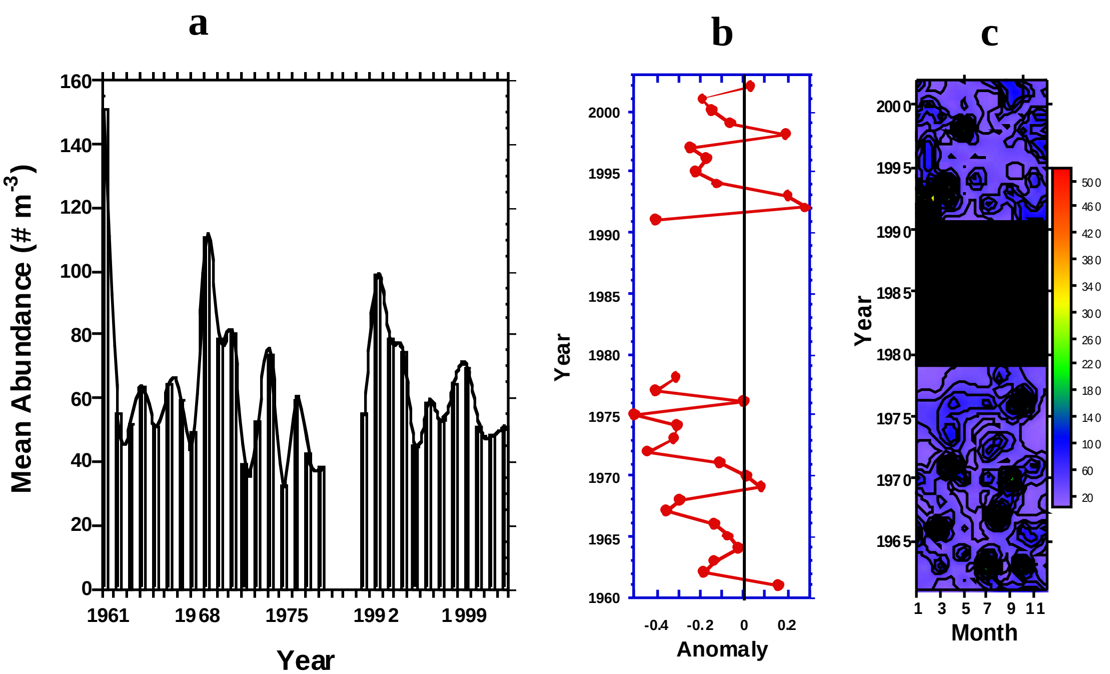

Fig. 13. Data presentation as in Figure 3 for *Paracalanus-Pseudocalanus* sp.

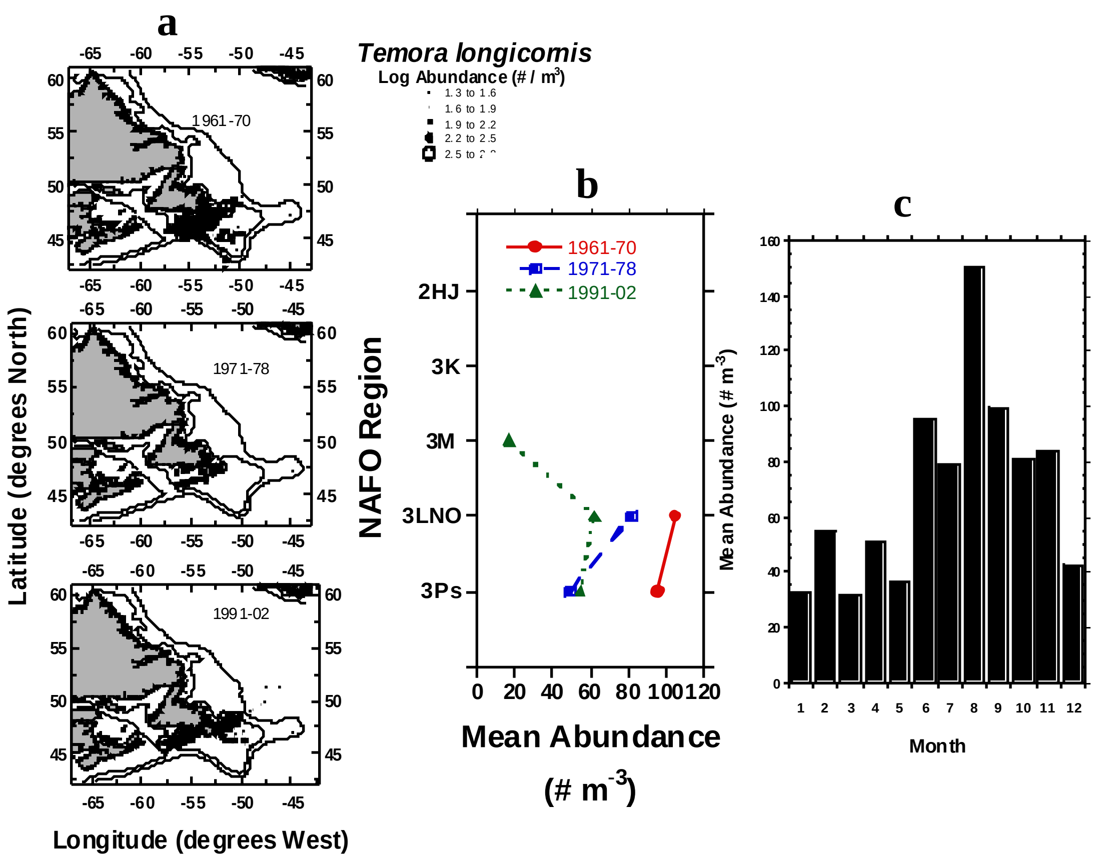

Fig. 14. Data presentation as in Figure 2 for *Temora longicornis*.

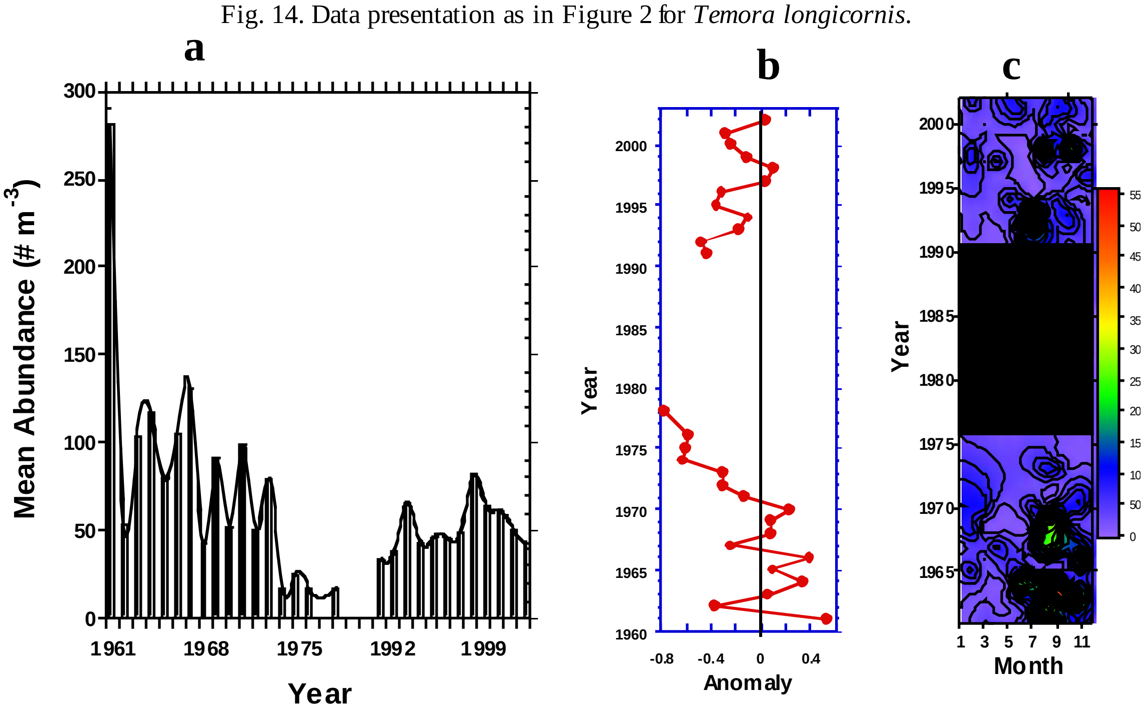

Fig. 15. Data presentation as in Figure 3 for *Temora longicornis*.

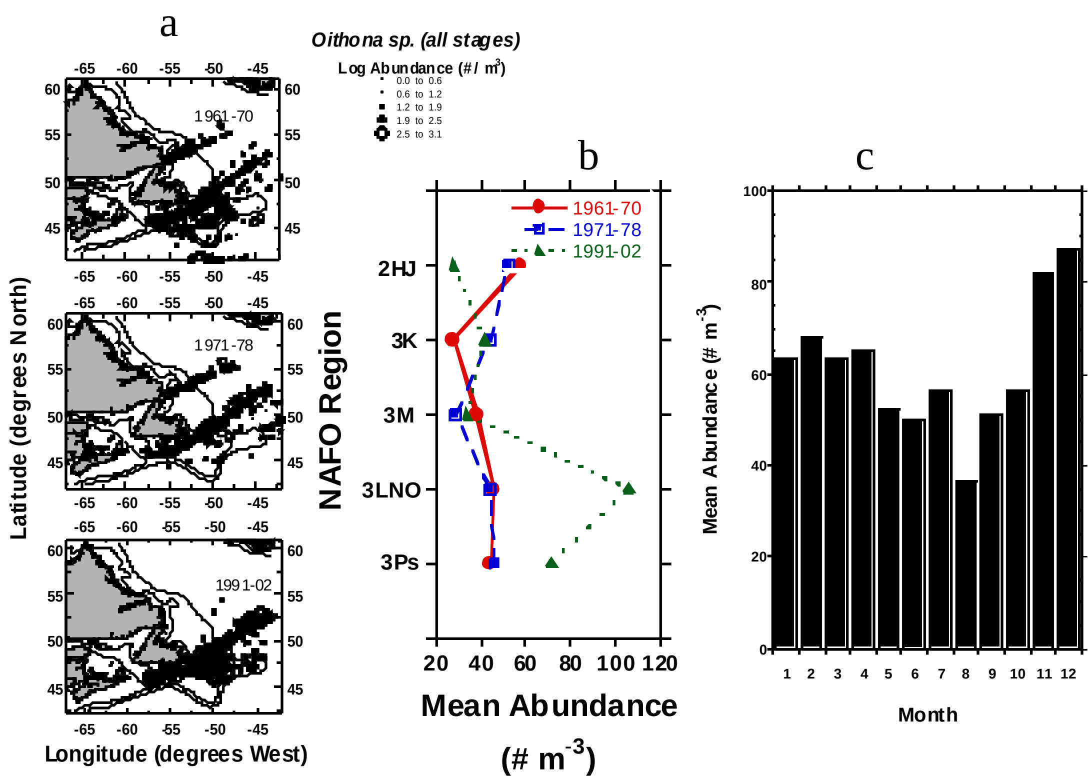

Fig. 16. Data presentation as in Figure 2 for *Oithona* sp.

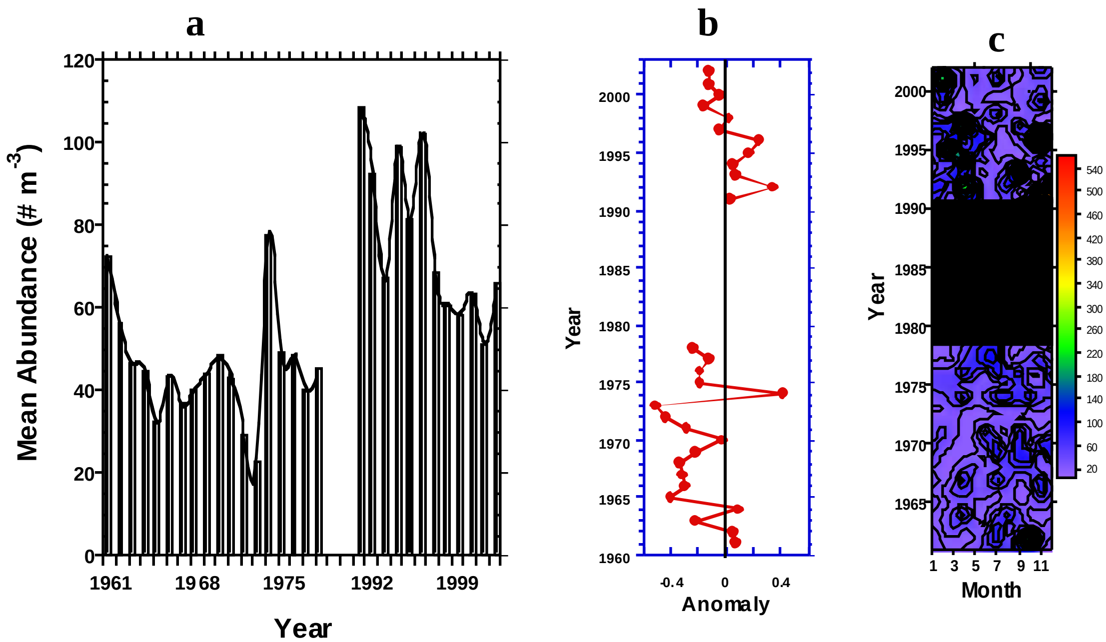

Fig. 17. Data presentation as in Figure 3 for *Oithona* sp.

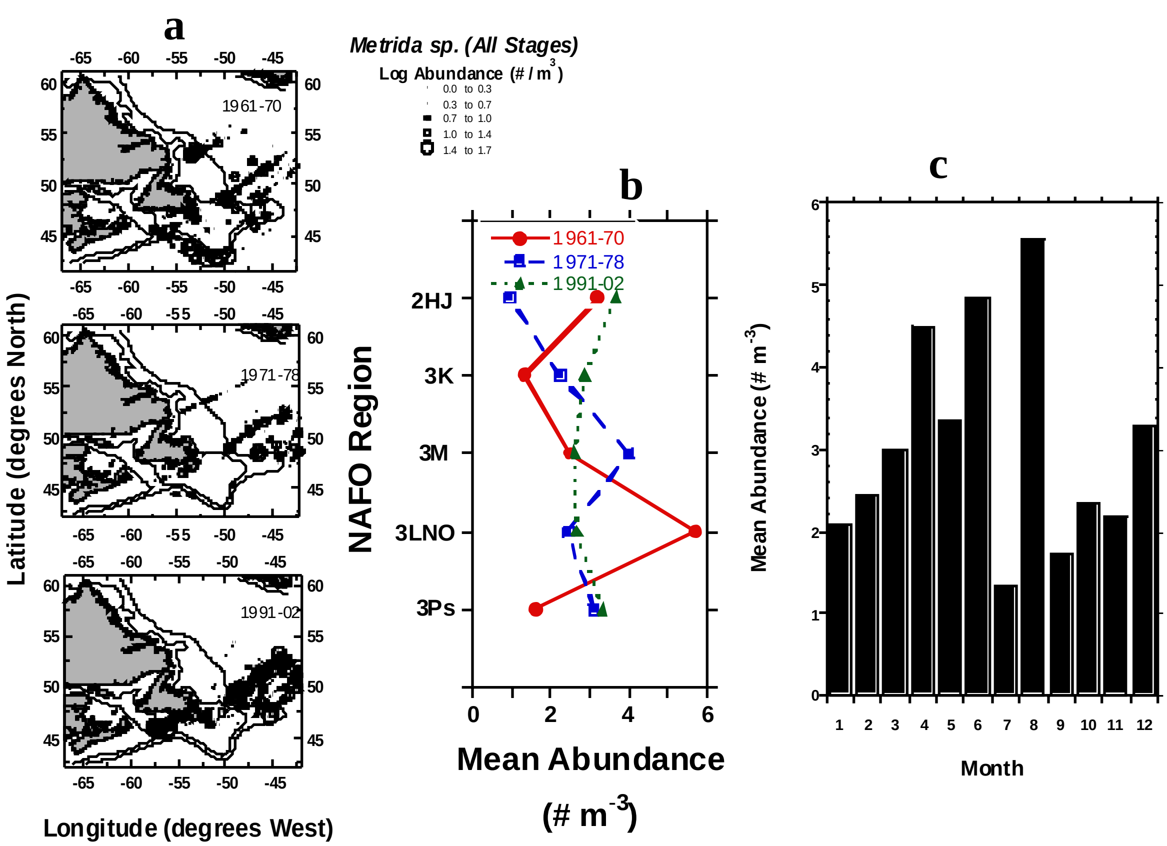

Fig. 18. Data presentation as in Figure 2 for *Metrida* sp.

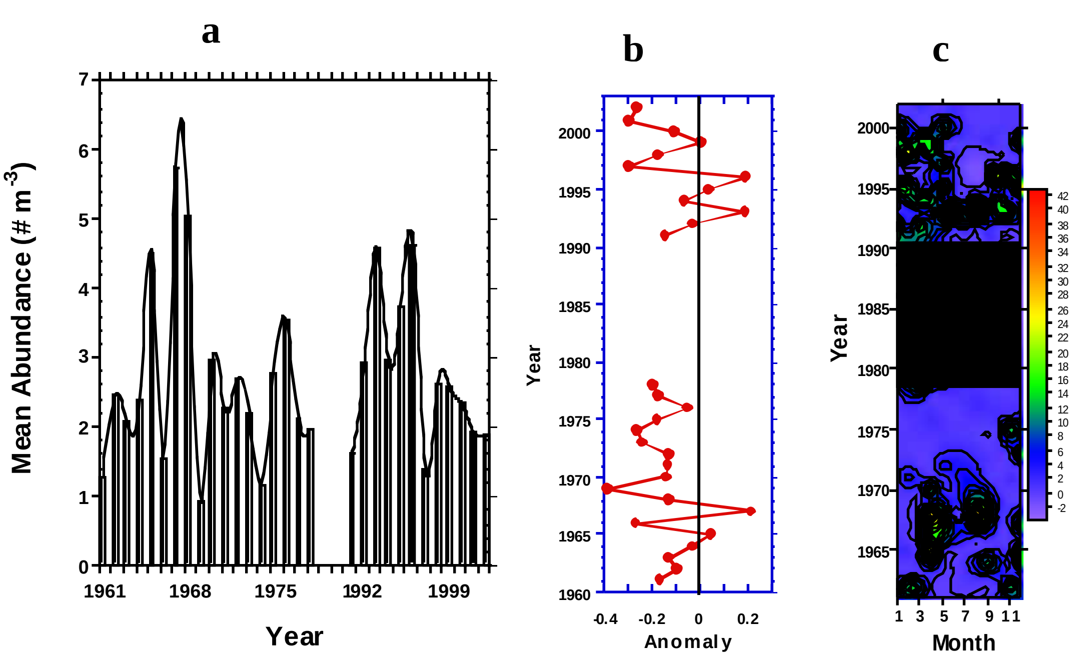

Fig. 19. Data presentation as in Figure 3 for *Metrida* sp.

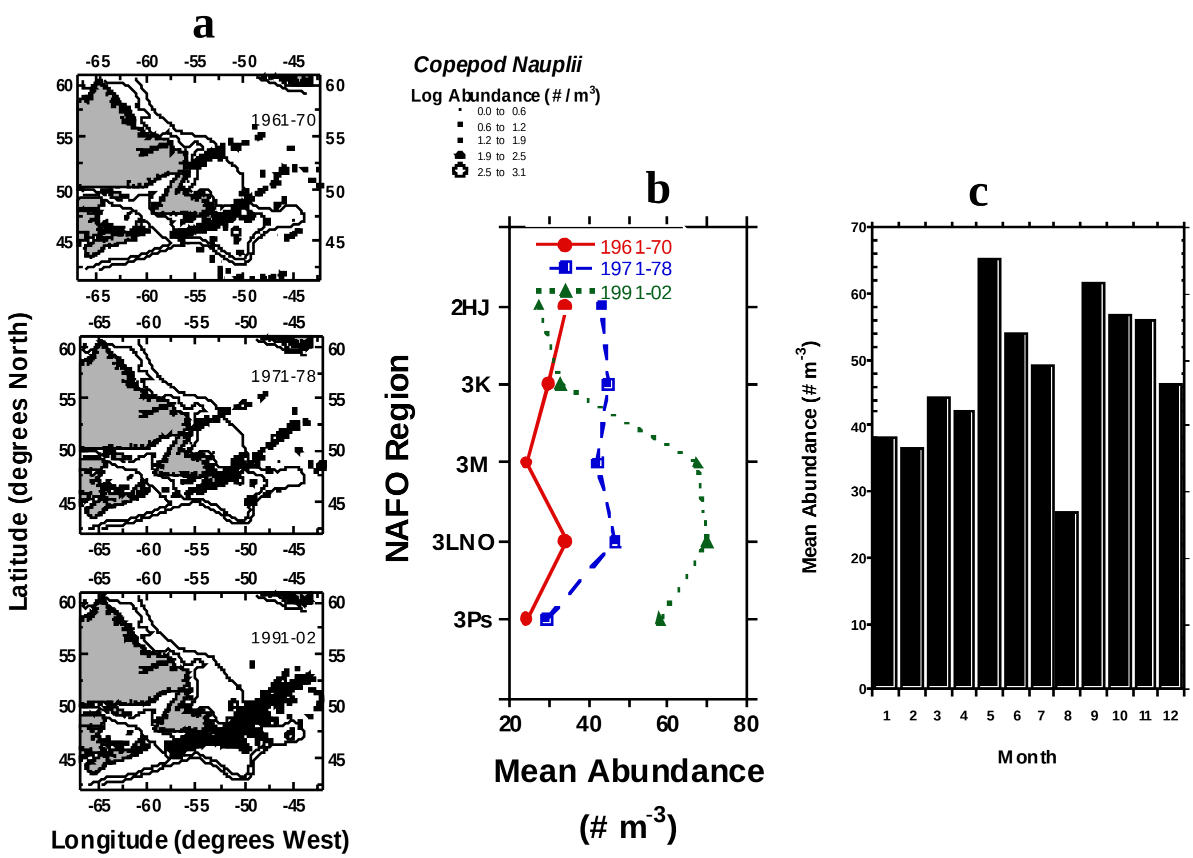

Fig. 20. Data presentation as in Figure 2 for copepod nauplii.

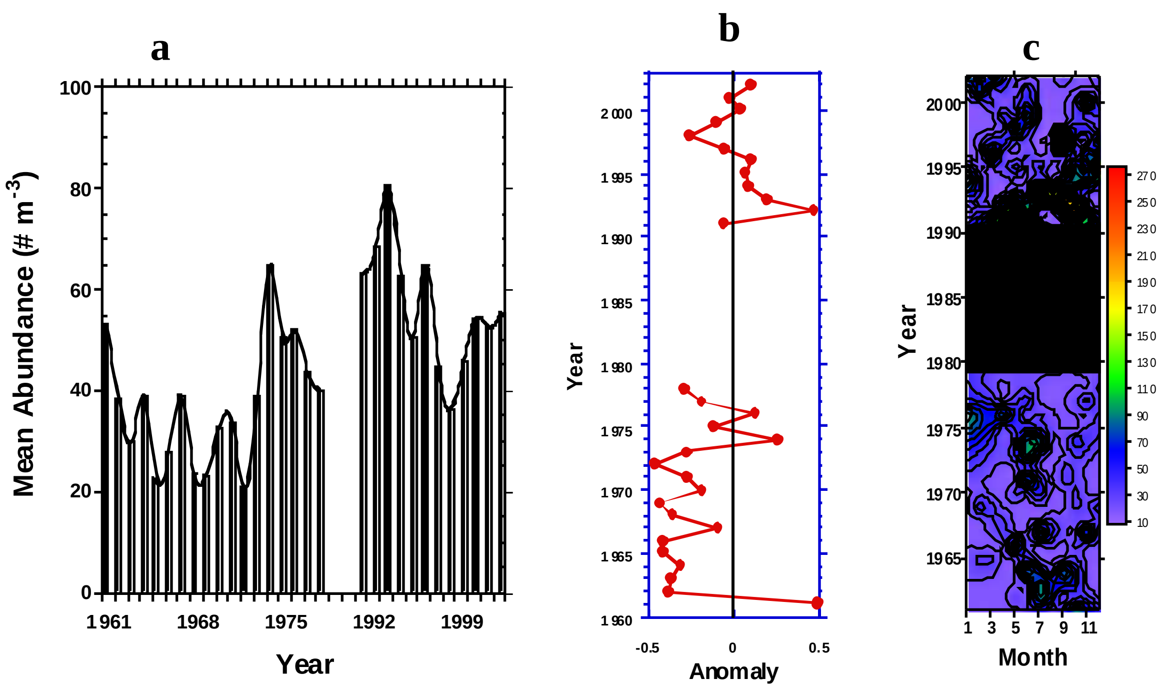

Fig. 21. Data presentation as in Figure 3 for copepod nauplii.

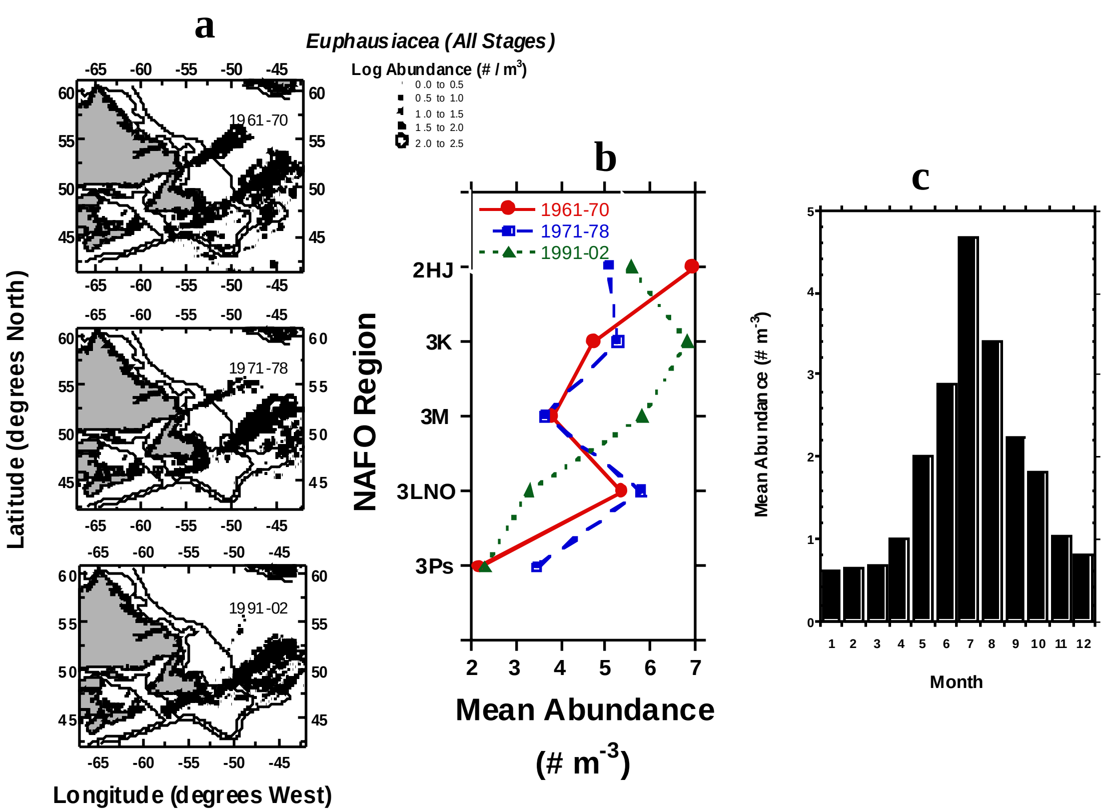

Fig. 22. Data presentation as in Figure 2 for Euphausiacea.

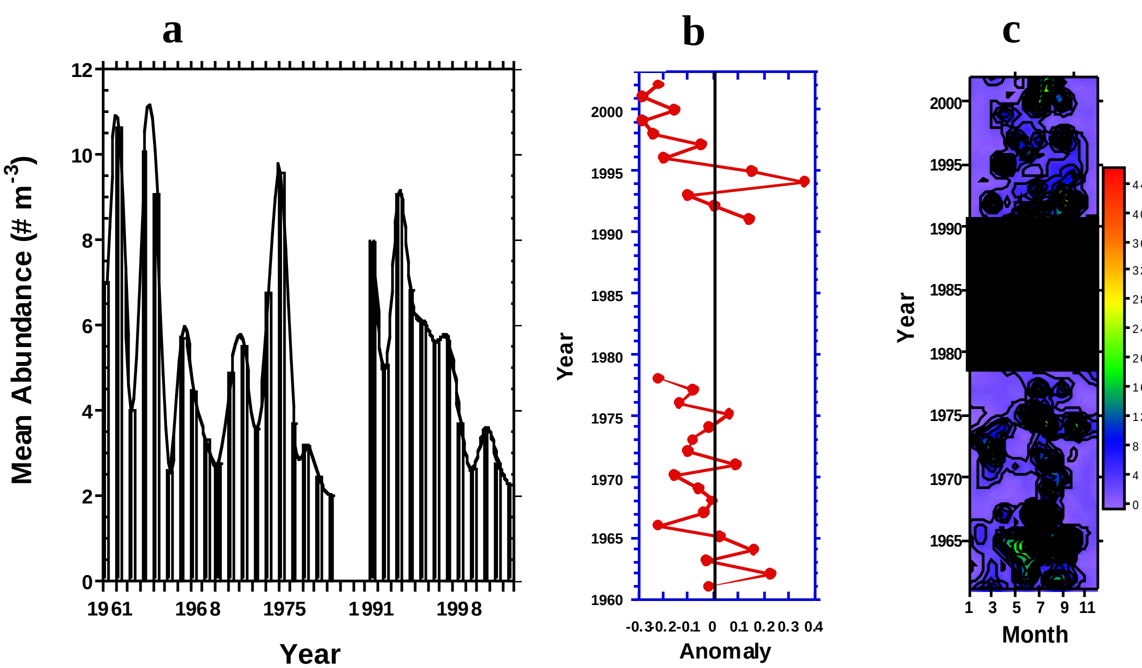

Fig. 23. Data presentation as in Figure 3 for Euphausiacea.

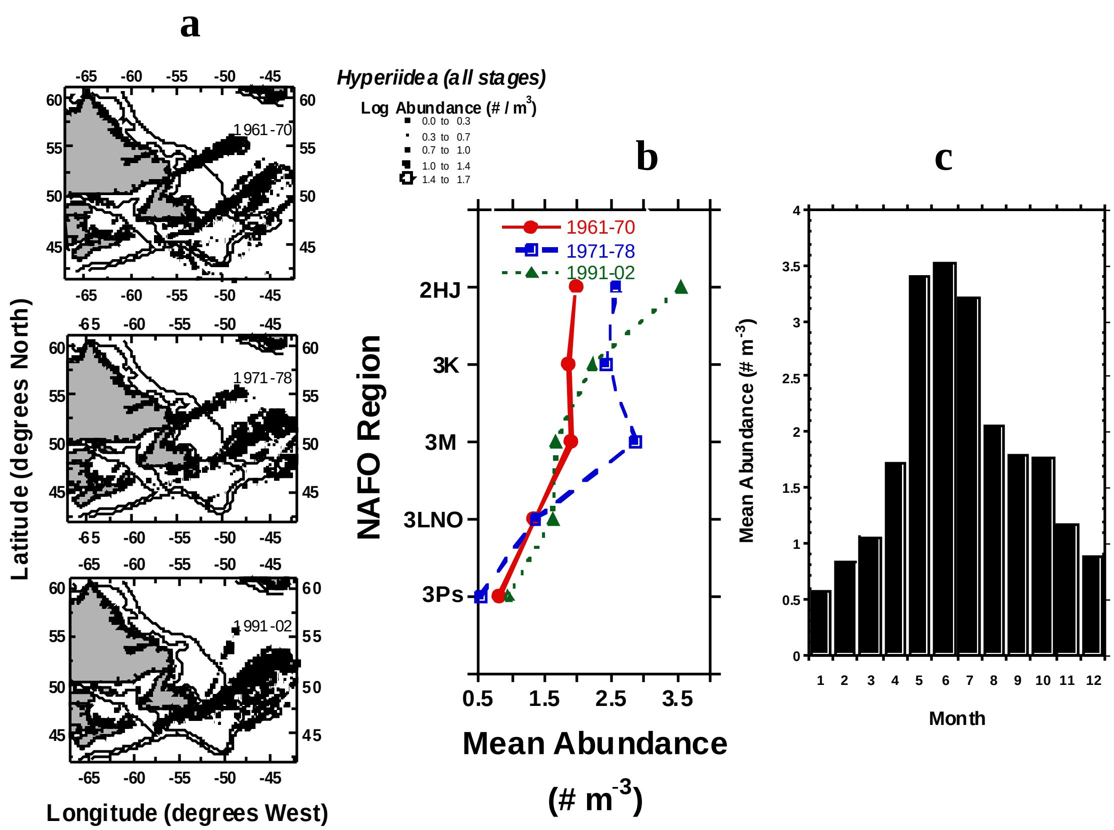

Fig. 24. Data presentation as in Figure 2 for Hyperiidea.

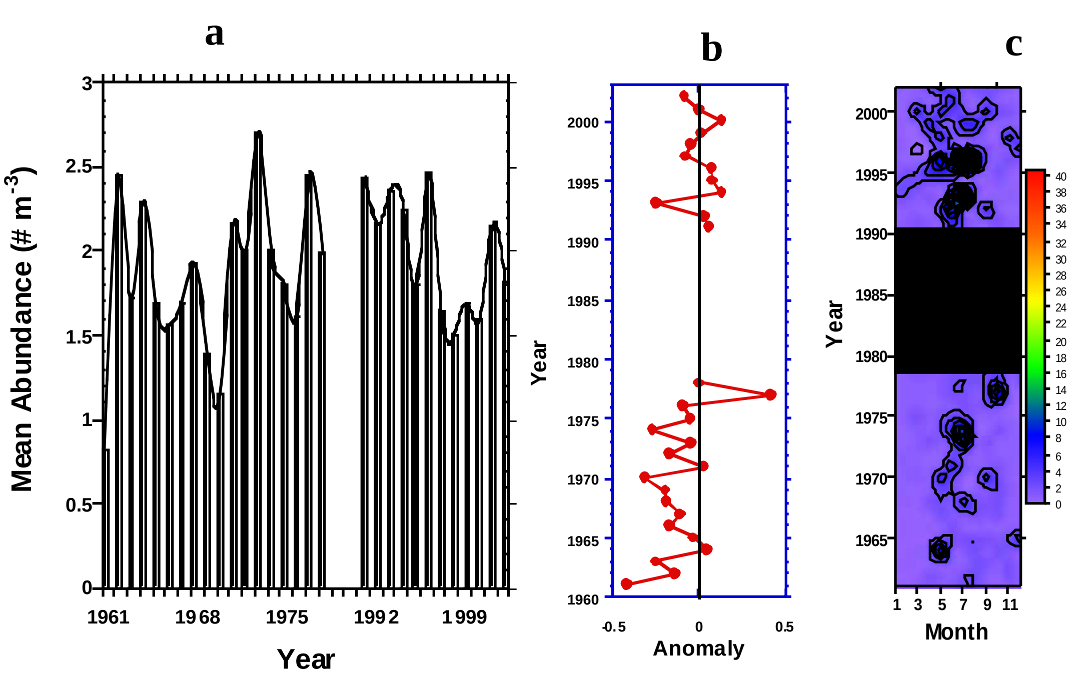

Fig. 25. Data presentation as in Figure 3 for Hyperiidea.

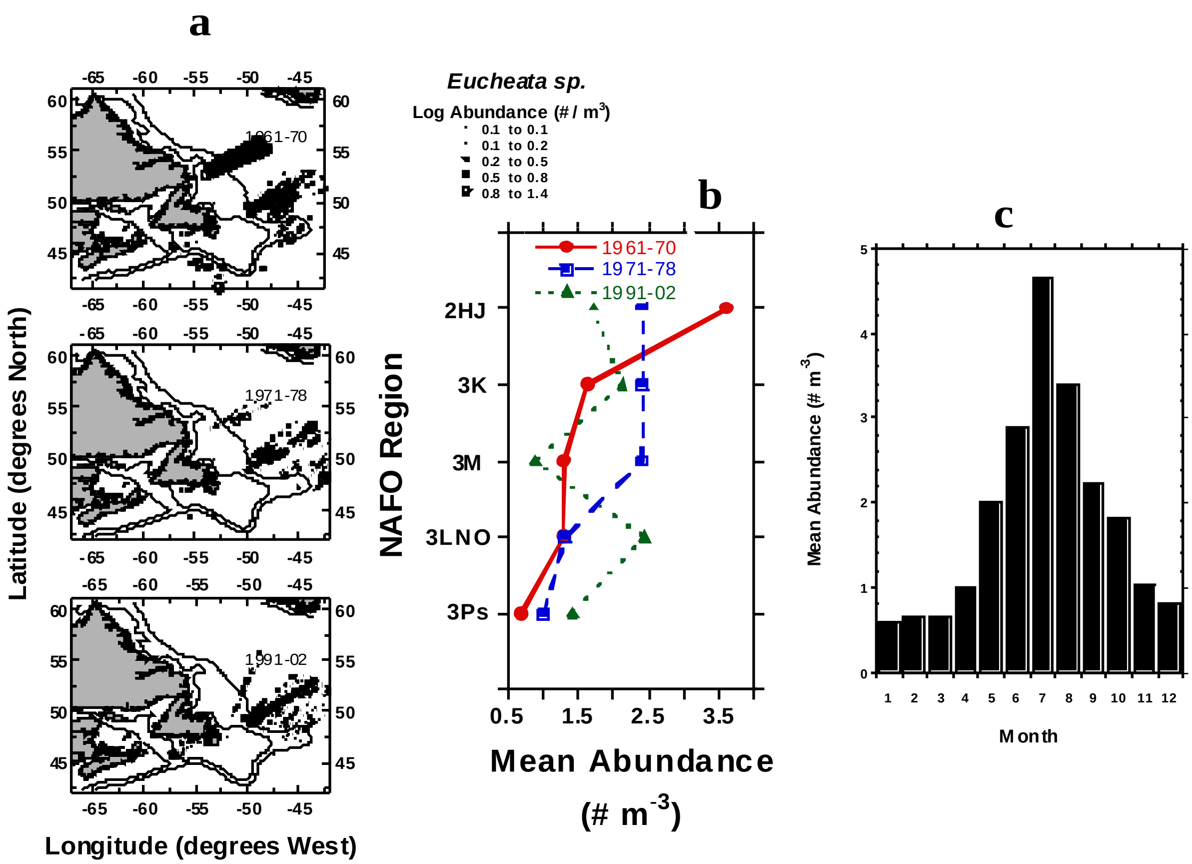

Fig. 26. Data presentation as in Figure 2 for *Eucheata* sp.

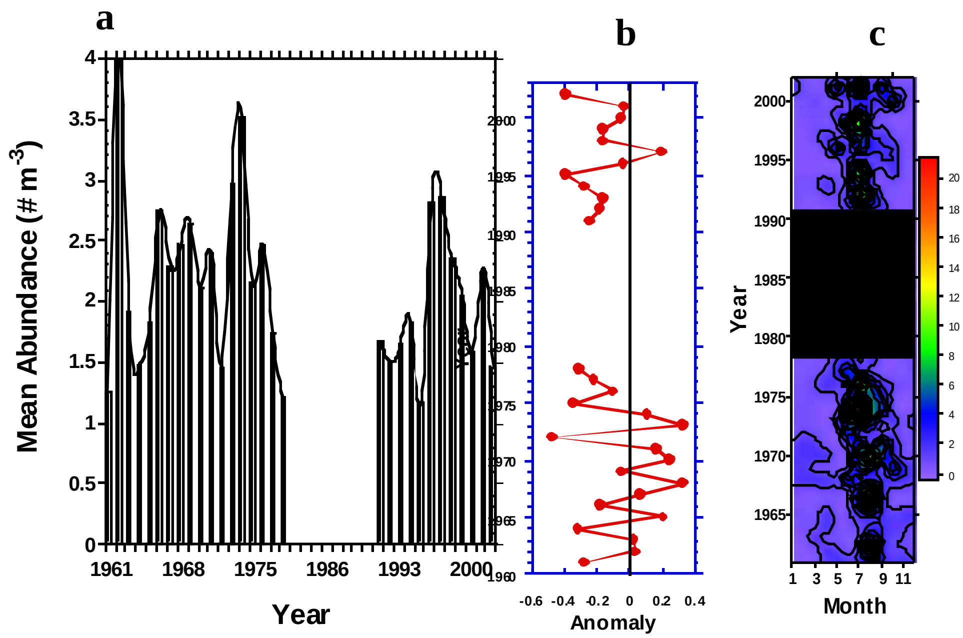

Fig. 27. Data presentation as in Figure 3 for *Eucheata* sp.

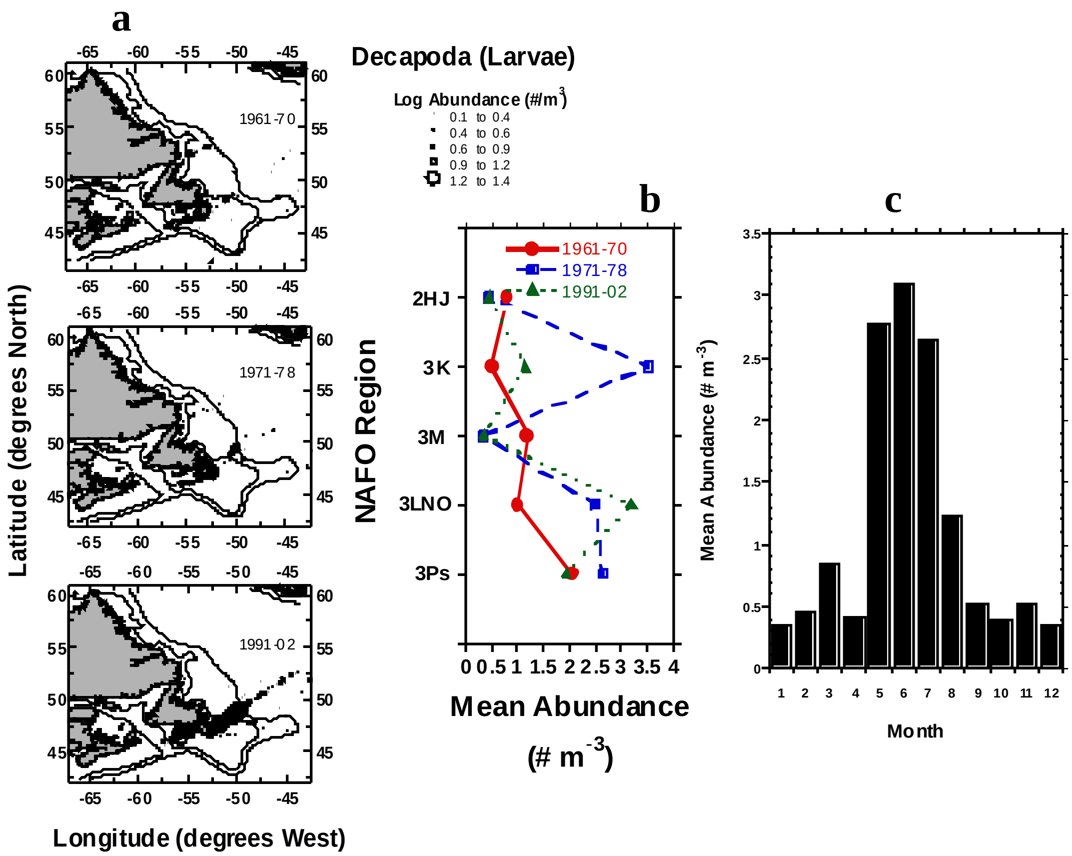

Fig. 28. Data presentation as in Figure 2 for Decapoda.

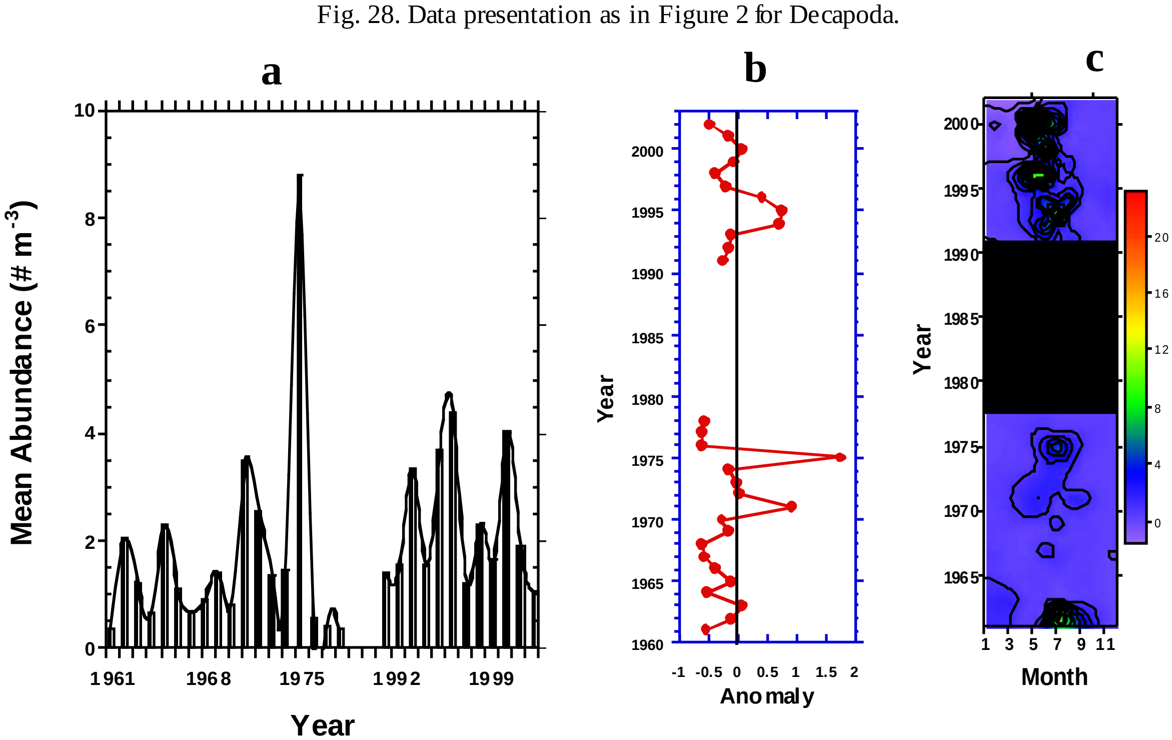

Fig. 29. Data presentation as in Figure 3 for Decapoda.

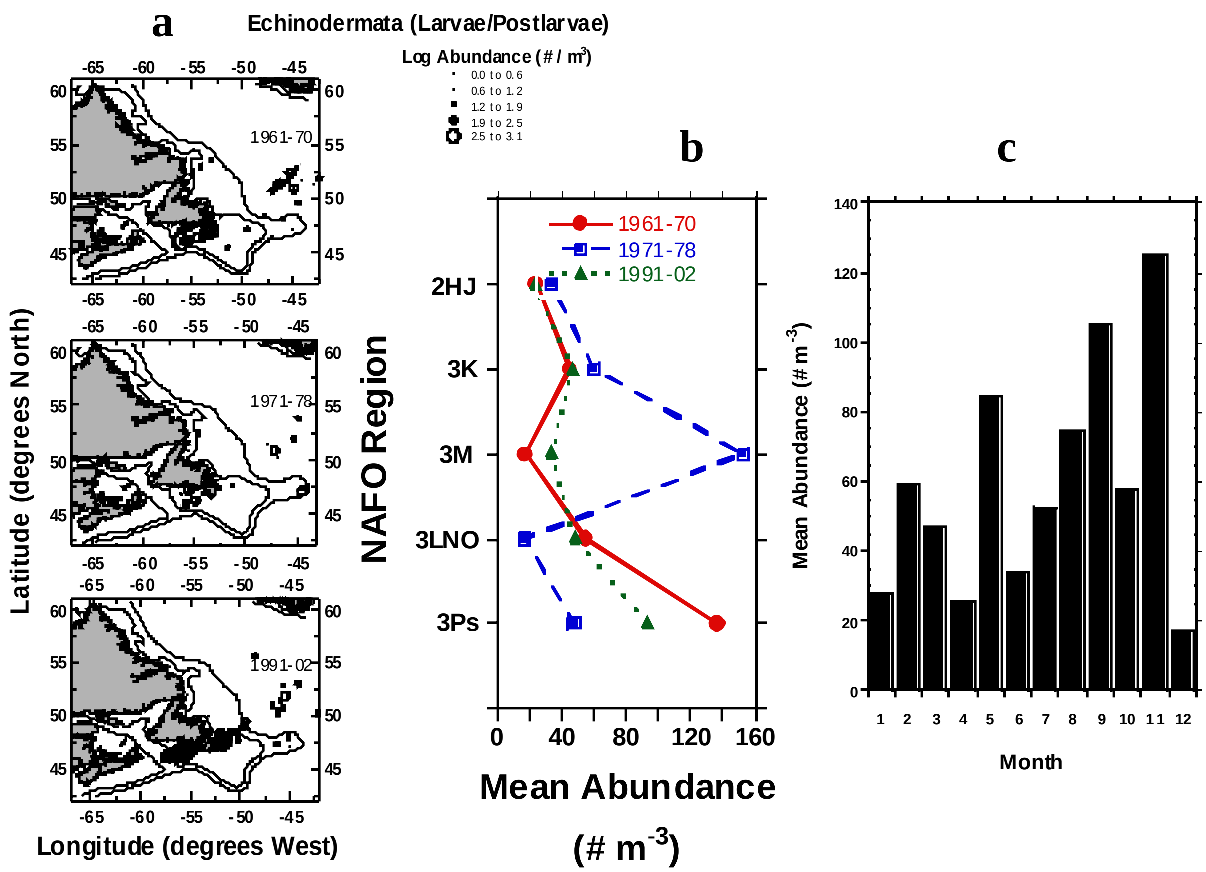

Fig. 30. Data presentation as in Figure 2 for Echinodermata..

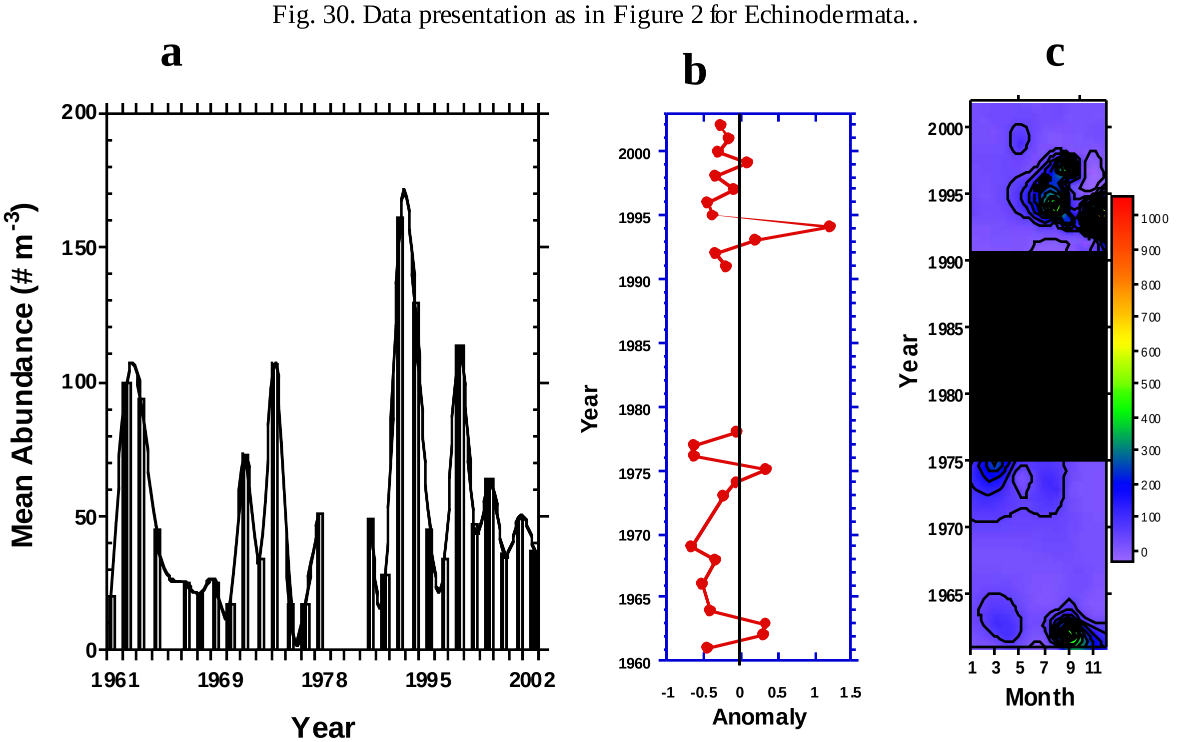

Fig. 31. Data presentation as in Figure 3 for Echinodermata..

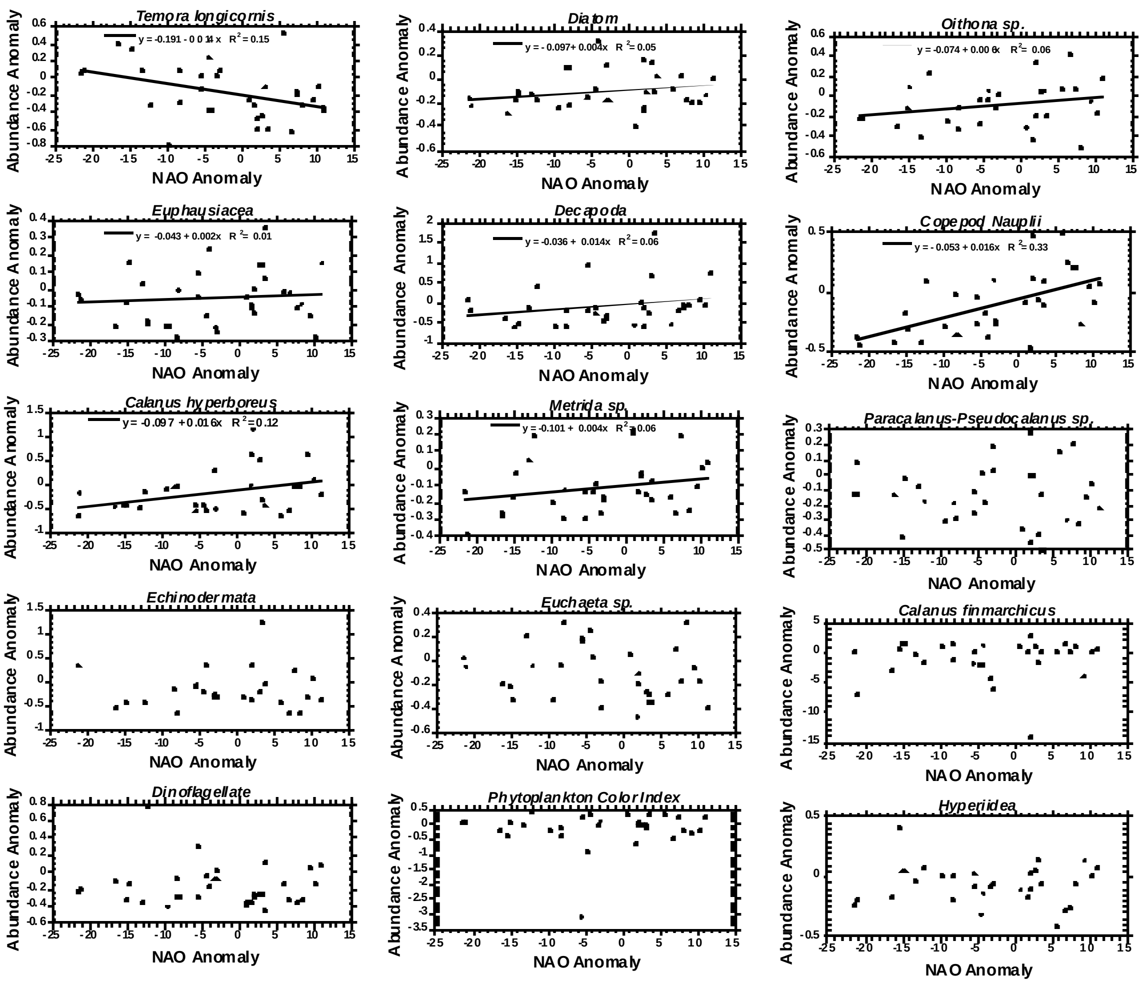

Fig. 32. Relationship between the annual North Atlantic Oscillation (NAO) index anomaly (referenced to the 1971-2000 mean), and the annual abundance anomalies (standardized) from the CPR taxa examined during 1961 to 2002.