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Ecosystem monitoring in the Northwest Atlantic: Canada's Atlantic Zonal Monitoring Program (AZMP)

By

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Abstract

The Canadian Department of Fisheries and Oceans (DFO) has the mandate to provide the environmental datasets that are necessary to track and predict changes in ocean state and productivity, to respond to questions posed by end-users, to alert them to short and long-term environmental/ecosystem changes, and to provide adequate historical databases to address future issues. In that context, DFO designed and implemented an ecosystem observing program for the Northwest Atlantic in 1998 that builds upon existing monitoring activities in the region. The Atlantic Zonal Monitoring Program (AZMP) represents a *minimum* effort to detect and follow climate change and variability in the Northwest Atlantic while increasing Canada's capacity to understand, describe, and forecast the state of the marine ecosystem and to quantify the changes in ocean physical, chemical and biological properties and the predator-prey relationships of marine resources.

The AZMP derives its information on the state of the marine ecosystem from data collected at a network of sampling locations (fixed point stations, cross-shelf transects, groundfish surveys, satellite remote-sensing) sampled at a frequency of bi-weekly to annually. Information on the relative abundance and community structure of plankton is also collected on long survey lines from Iceland to Newfoundland and Newfoundland to the Gulf of Maine from commercial ship traffic instrumented with the Continuous Plankton Recorder (CPR).

The AZMP sampling design provides basic information on variability in physical (temperature, salinity, ocean optics, sea-level), chemical (nutrients, oxygen) and biological (chlorophyll, plankton abundance and species) properties of the Canadian Atlantic continental shelf. Groundfish surveys and cross-shelf transects provide detailed regional geographic information but are limited to seasonal coverage at best. Critically placed fixed stations complement the geography-based sampling by providing more detailed information on temporal (seasonal) changes in ecosystem properties. Satellite remote-sensing of sea-surface phytoplankton biomass (chlorophyll) provides the large scale (zonal) perspective on important environmental and ecosystem variability. The CPR lines provide information on large scale (inter-regional) and long-term (yearly to decadal) variability in plankton abundance and community structure. Ongoing groundfish surveys provide distribution and abundance estimates for commercial and non-commercial finfish and invertebrates.

Observations from the first three years of AZMP operation and historical data are providing a clear picture of the scales of natural ecosystem variability in the region and new evidence that links biological variability with changes in physical and chemical environmental properties. Links between indices of groundfish recruitment and environment/ecosystem variability are also being explored.

Key Words: Monitoring, ecosystem, Northwest Atlantic, continental shelf, plankton, remote-sensing, CPR, groundfish, recruitment.

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INTRODUCTION

Harvest fisheries in the Northwest Atlantic, notably the northern cod (*Gadus morhua*) and other commercially important groundfish and pelagics, have gone through dramatic changes in the past two decades (Myers et al. 1997; Sinclair et al. 1997). Although fishing mortality is undoubtedly a leading cause of declines in abundance and changes in size structure and composition, the role of environment in these changes, including population recovery (or the lack thereof), has not been adequately assessed. Indeed, during the period of most rapid changes (decline) in cod populations, only a rudimentary environmental monitoring effort was in place in the Northwest Atlantic off the coast of Canada and was comprised largely of physical measurements, i.e. temperature, salinity. The inability of scientific experts to provide resource regulatory agencies within the Canadian federal government informed advice on the influence of environment on regional fish stock dynamics and the broadened mandate of these agencies to implement an "ecosystem approach" to resource management, prompted the DFO to design and institute a systematic and comprehensive ecosystem monitoring program for Canadian Atlantic coastal waters. Augmentation of the chemical and biological components of the observation program, in particular, were identified as a priority.

The Northwest **A**tlantic **Z**onal **M**onitoring **P**rogram (AZMP) began in 1998 (Therriault et al. 1998) with all observational components fully operational by 1999. The AZMP was designed to build upon existing regional monitoring activities with the view of meeting at least *minimum* requirements: to detect and follow climate change and variability in the Northwest Atlantic; to increase Canada's capacity to understand, describe, and forecast the state of the marine ecosystem; and, to quantify the changes in ocean physical, chemical and biological properties and the predator-prey relationships of marine resources.

Three complete years of data have been collected and analysed and progress is being made in condensing the mass of raw data into data products useful in describing the natural scales of variability of the NW Atlantic ecosystem. Efforts are also underway to link environmental variability with dynamics of groundfish populations. Some examples from the Scotian Shelf are provided to illustrate the nature and quality of data products being produced by the AZMP and to illustrate one of a number of approaches under consideration to explore environmental effects on fisheries.

METHODS

The AZMP covers a large geographic area and for that reason requires the co-ordinated effort of four federal government administrative regions: the Newfoundland Region covering the northern sector (Grand Banks to northern Labrador coast), the Maritimes Region covering the southern sector (Gulf of Maine and Scotian Shelf), and the Quebec and Gulf Regions covering the western sector (Gulf of St. Lawrence). The AZMP derives its information on the state of the marine ecosystem from data collected at a network of sampling locations (fixed point stations, cross-shelf transects and groundfish surveys) sampled at a frequency of bi-weekly to annually (Fig. 1). Field observations are supplemented by zonally synoptic satellite remote-sensing data (sea surface temperature and ocean colour) generated as composite images twice monthly. Data on the relative abundance and community structure of plankton are also collected on long survey lines from Iceland to Newfoundland (Line Z) and Newfoundland to the Gulf of Maine (Line E) from commercial ship traffic instrumented with the Continuous Plankton Recorder, CPR (http://www.npm.ac.uk/sahfos/sahfos2.html).

The AZMP sampling design provides basic information on variability in physical (temperature, salinity, ocean optics, sea-level), chemical (nutrients, oxygen) and biological (chlorophyll, plankton abundance and species) properties of the Canadian Atlantic continental shelf. Groundfish surveys and cross-shelf transects provide detailed regional geographic information but are limited in their seasonal coverage (once or twice annually). Critically placed fixed stations complement the geography-based sampling by providing more detailed information on temporal (bi-weekly) changes in ecosystem properties. Satellite remote-sensing provides the high-resolution, large spatial scale perspective on important environmental and ecosystem variability and the CPR lines provide information on large scale (inter-regional) and long-term (yearly to decadal) variability in plankton abundance and community structure; the CPR lines in the Northwest Atlantic have run (with notable gaps) since the late 1950s / early 1960s.

The AZMP has formal reporting procedures that include the timely transfer of data and data products to the national AZMP website (http://www.meds-sdmm.dfo-mpo.gc.ca/zmp/main_zmp_e.html) and the annual production of a series of Canadian government Research Documents and Stock Status Reports (http://www.dfo-mpo.gc.ca/csas/Csas/English/Publications/Index_Pub_e.htm) among other reporting activities.

RESULTS

Fixed-stations. AZMP's strategically located fixed-stations have provided a wealth of new information on the growth cycle and community structure of plankton populations of the Northwest Atlantic and the influence of ocean physics and chemistry on these biological properties. The contoured plots of temperature for the Halifax station from 1999-2001, for example, show the springtime thermocline development and seasonal horizontally and vertically deepening with near surface temperatures attaining their highest values in 1999 (Fig. 2, top panel). The most extensive and longest lasting cold intermediate layer occurred in 2001 with temperatures <4^{o}C found between 50 and 100 m throughout the year. Nitrate reached highest seasonal levels (~ 8 µM) in the near surface layer in late winter (Fig. 2, middle panel). Year-to-year variability in the (wintertime) build up of nitrate was also evident. This store of nitrate is quickly depleted in spring, resulting in a long period (>6 months) of near surface concentrations of near zero. Deep intrusions (upwelling) of waters high in nitrate occurred throughout the year but appeared particularly strong in 2000. Phytoplankton biomass (chlorophyll) exhibited considerable high frequency variability superimposed on a strong seasonal cycle marked by a pronounced spring "bloom" (Fig. 2, bottom panel). The timing and magnitude of the spring bloom showed significant inter-annual variability; peak concentrations were ~8 mg m^{-3} in 2000 and only ~2 mg m^{-3} in 2001 and the bloom in 1999 was earlier (by at least two weeks) than in 2000 or 2001. Phytoplankton community composition (no shown) was characterized by a general succession from diatom dominance in spring (>80%) to flagellate dominance (>60%) in late summer and fall; this general successional pattern was seen in all years.

Total zooplankton abundance at the Halifax station (not shown) was also marked by high frequency variability; no clear season cycle was evident. Of the major zooplankton groups identified, copepods dominated numerically (>80%) year-round in all years (Fig. 3, top panel). A clear seasonal succession was evident in the composition of the copepod fraction, dominated by larger species (i.e. *Calanus spp*.) in spring and smaller species (e.g. *Oithona spp*., *Centropoges spp., Pseudocalanuc spp.)* the rest of the year (Fig. 3, middle panel). A strong and recurring seasonal cycle was apparent in the timing of reproduction of the dominant calanoid, *Calanus finmarchicus*, as evidenced by the appearance of the younger developmental stages in spring (Fig. 3, bottom panel). The timing and duration of reproduction varied significantly by year; reproduction was particularly strong in 1999 and began earlier than in 2000 or 2001, as did the phytoplankton bloom.

Groundfish surveys. The annual groundfish surveys provide information on shelf-wide mesoscale variability of near surface and bottom physical, chemical and biological properties useful for habitat mapping and in fish distribution studies. The July Scotian Shelf surveys illustrate some of the large scale, inter-annual variations being observed. In 1998, for example, the intrusion of Labrador Slope Water onto the Scotian Shelf resulted in lower bottom water nitrate concentrations than normal (Fig. 4). Labrador Slope water is also characterized by colder temperatures, lower salinity and higher oxygen concentrations than shelf and local slope waters. The main avenue for these intrusions is through a deep area between banks on the central Shelf. This is particularly evident in the 1999 and 2000 contoured plots; conditions in these years were closer to "normal". Warm Slope Water with its relatively high nutrient levels displaced the Labrador Shelf water in these years. The low concentrations of nitrate were also found in the eastern Gulf of Maine in 1998. Lower-than-normal bottom water temperatures, salinity and nitrate concentrations were also evident in the 2001 survey.

Cross-shelf transects. The AZMP transects provide information on vertical structure and cross-shelf mesoscale variability in ocean properties at different seasons. Chlorophyll transects on the Halifax Line from different years, for example, can be combined to generate a pseudo-annual phytoplankton cycle (Fig. 5). Beginning in April and early May, these transects illustrate the early high biomass during the spring bloom in the near surface layer that evolves into lower biomass and weak sub-surface maximum chlorophyll concentrations in the late spring. Low biomass predominates throughout the summer into the fall when there are generally minimal concentrations across the entire shelf. A modest fall bloom occurs in the late fall when surface waters are recharged with nutrients.

Satellite remote-sensing. Satellite remote-sensing provides unprecedented detail on both temporal and spatial variability of selected physical and biological properties of surface waters on the large scale. For example, the NOAA (SST) and SeaWiFS (chlorophyll) data along the AZMP Halifax section have been extracted and colourcoded to show scales of variability for the period 1998-2001. The SST plots show clearly the seasonal warming and cooling cycles of surface waters (Fig. 6A). Evident also are significant year-to-year variations in the temperature cycle, e.g. surface waters were warmer and warm conditions lasted longer in 1999 compared with 2000. The overwhelming characteristic of the surface chlorophyll is the spatial and temporal variability (Fig. 6B). Contrast, for example, the spring bloom in 1999 with 2001. In 1999, there was an early bloom (February-March) on the inner shelf and over the outer bank (as seen at the Halifax fixed-station); in 2001 the bloom was later (March-April) and occurred over the inner basin and slope. The timing of the blooms was different and the spatial patterns were opposite – areas of high chlorophyll in one year were low in the other.

Continuous Plankton Recorder (CPR). The CPR is the longest data record available on plankton in the Northwest Atlantic and provides the only information available on biological variability on the decadal time-scale. Phytoplankton colour index and abundance of large diatoms and dinoflagellates on the Scotian Shelf increased notably in the early 1990s (continuing into the 2000s) compared with levels seen in the 1960s and early 1970s (Fig. 7A). There also appears to have been a shift towards an earlier and more prolonged seasonal (spring) peak in abundance in recent years (Fig. 7B). A similar shift to earlier months in the seasonal maximum of the dominant mesozooplankton, *Calanus finmarchicus,* was also apparent, however, overall abundance decreased in the 1990s compared with the 1960s and 1970s. Zooplankton appear to be recovering from the low levels observed in the early 1990s.

Recruitment indices. In addition to developing a basic description of the state of the environment of the Northwest Atlantic, the AZMP is endeavouring to understand the link between environmental variability and the dynamics of commercial fish populations. As a first step in exploring these linkages, the AZMP is compiling a recruitment time-series database for finfish and invertebrates across the four regions of the Atlantic Zone, including spawning stock biomass and growth estimates (the latter restricted to commercial species with age data). From these data, three indices are being produced: recruitment, recruitment rate and the residuals from stock-recruitment relationships. The latter index (pattern in S-R residuals) is interpreted as the contribution of environment effects on recruitment variability. Progress on the development of the database and time-series of the indices (recruitment, recruitment rate, residuals from the S-R relationship) for one of the important commercial groundfish species on the Scotian Shelf, haddock, is given for illustration (Fig. 8). Where multiple stocks of a given species occurred, inter-stock comparisons were made. For example, the three haddock stocks distributed across the Scotian Shelf/Georges Bank region appear to be responding in unison to environmental effects, based on the high degree of coherence in the temporal series of S-R residuals (Fig. 9A). In contrast, cod stocks distributed over the same geographic areas appear to be responding independently to environmental forcing (Fig. 9B). The intention is to apply this methodology to a wide variety of stocks and it is anticipated that the database and derived indices will ultimately provide a description of the "State of Fishery Production" for analysis and evaluation in relation to specific environmental and ecosystem data products generated by the AZMP.

DISCUSSION

Data management and production of data products (generic and custom) have become a high priority activity as the AZMP matures. Data products are designed to distil the mass of raw data into more concise, ecologically relevant "indices" or "indicators". These products facilitate communication of observational results to end-users, including non-specialists, and are essential components of ecosystem-based resource monitoring and management (Sinclair et al. 1999; O'Boyle, 2000; Jamieson and O'Boyle, 2001; Harrison and Sinclair, 2001). Additionally, indices or indicators may be preferable to primary observational data in linking environmental/ecosystem conditions to living marine resource variability (Harrison and Sameoto, 1996; Halliday et al. 2001).

Physical indices. Considerable progress has been made in developing common sets of standardized indices for physical properties of the ocean and atmosphere in the Northwest Atlantic (Colbourne et al. 2002). These include large-scale meteorological indices such as time-series of: (1) the NAO; (2) air temperature; and, (3) winds at fixed sites, and their anomalies. Oceanography features include time-series and anomalies of: (4) coastal drainage basin features (freshwater discharge from major regional river systems); (5) regional ice conditions (duration, integrated area, iceberg count); (6) regional SST (sea surface temperature); and, other temperature/salinity data products (e.g. bottom temperatures, cold intermediate layer [CIL] area, position of major ocean fronts, e.g. Gulf Stream, shelf/slope front, stratification indices).

Development of chemical/biological indices for the Northwest Atlantic is less well advanced (Harrison and Sameoto, 1996) although progress is being made at the international level (ICES, 2001). Not only are specific chemical/biological indices under consideration but also physical indices that have direct relevance to chemical/biological processes. For example, incident solar radiation and ocean optical properties (e.g. euphotic depth) as well as mixed-layer depth strongly influence the timing of onset of the spring phytoplankton bloom in north temperate waters. Stratification, in turn, regulates the mixing of nutrients to the upper ocean and sets limits on summertime primary production and influences the vertical structure of plankton and well as the timing of the fall phytoplankton bloom. Stratification may also play a role in the survival and dispersion of plankton stages of higher trophic level biota (invertebrates and vertebrates).

Chemical indices. Chemical indices of importance include: (1) bottom water oxygen levels (or % saturation) that may define an important property of habitat and, along with temperature and salinity, may influence distributional patterns of marine biota at various trophic levels; (2) wintertime surface water nutrient (nitrate, phosphate, silicate) inventories that largely determine the magnitude and extent of the spring phytoplankton bloom; (3) nutricline depth and concentration gradient that are constraints on summertime surface nutrient supply and regulate primary production levels; and, (4) stoichiometry (e.g. nitrate:silicate ratio) that may influence body composition or community structure (species composition) of phytoplankton.

Biological indices. Biological indices include biomass properties, such as: (1) the onset, magnitude, geographic extent and duration of phytoplankton blooms; and, (2) timing and magnitude of zooplankton abundance peaks, in aggregate or by species. Indices based on community structure would include: (3) phytoplankton species ratios (e.g. diatoms:dinoflagellates) or size ratios (net:nano-phytoplankton); (4) zooplankton species (e.g. copepods:cladocera) or size ratios (large spp.:small spp); (5) developmental stage distributions within species for determining time of reproduction; and, (6) more conventional metrics of plankton community structure such as dominant and keystone species, species richness and other diversity statistics.

Analysis of the residuals of stock-recruitment relationships show promise in identifying 'environmental effects' on recruitment trends of commercial fish populations, however, the specific environmental properties at play are not revealed. The challenge for the immediate future is to determine how to use the myriad of environmental and ecosystem-based indices/indicators to describe and evaluate the state of the ocean and how to relate these properties to the dynamics of harvest fisheries. Simple aggregation techniques such as the "Score Card" approach and "Traffic Light Method", TLM (Halliday et al. 1999) are being explored and evaluated as well as more complex multivariate statistical approaches (Clarke and Warwick, 1994). In parallel, hierarchical approaches are also being employed to identify relevant environmental indicators through a process of "unpacking" where generalised ecosystem objectives are translated into observable and quantifiable environment/ecosystem properties (Jamieson and O'Boyle, 2001).

The AZMP is considering strategies for strengthening its communication and linkages with living marine resource managers and users. To this end, plans are underway to bring the parties of interest together to consider the following questions, a number of which are common with those identified in this ICES ASC 2002 theme session on fisheries and environmental management:

- What are the major influences of the environment on fish/shellfish distribution, behaviour, catchability and abundance estimates from commercial and research data?
- How does the environment affect population processes (e.g. growth, recruitment, egg production, etc.)?
- How can environmental information be incorporated into fisheries assessment: how might environmental models be used in stock assessment?
- What are the advantages and disadvantages of time-series analysis versus event or regime-shift analysis in determining effects of the environment on fish stocks?
- What stock-specific environmental indices can be derived from the data collected within the present AZMP?
- Are there measurements that are important for assessment purposes that the AZMP could be collected but is not?
- How can communication and co-operation between oceanographers and fisheries assessment scientists be improved?

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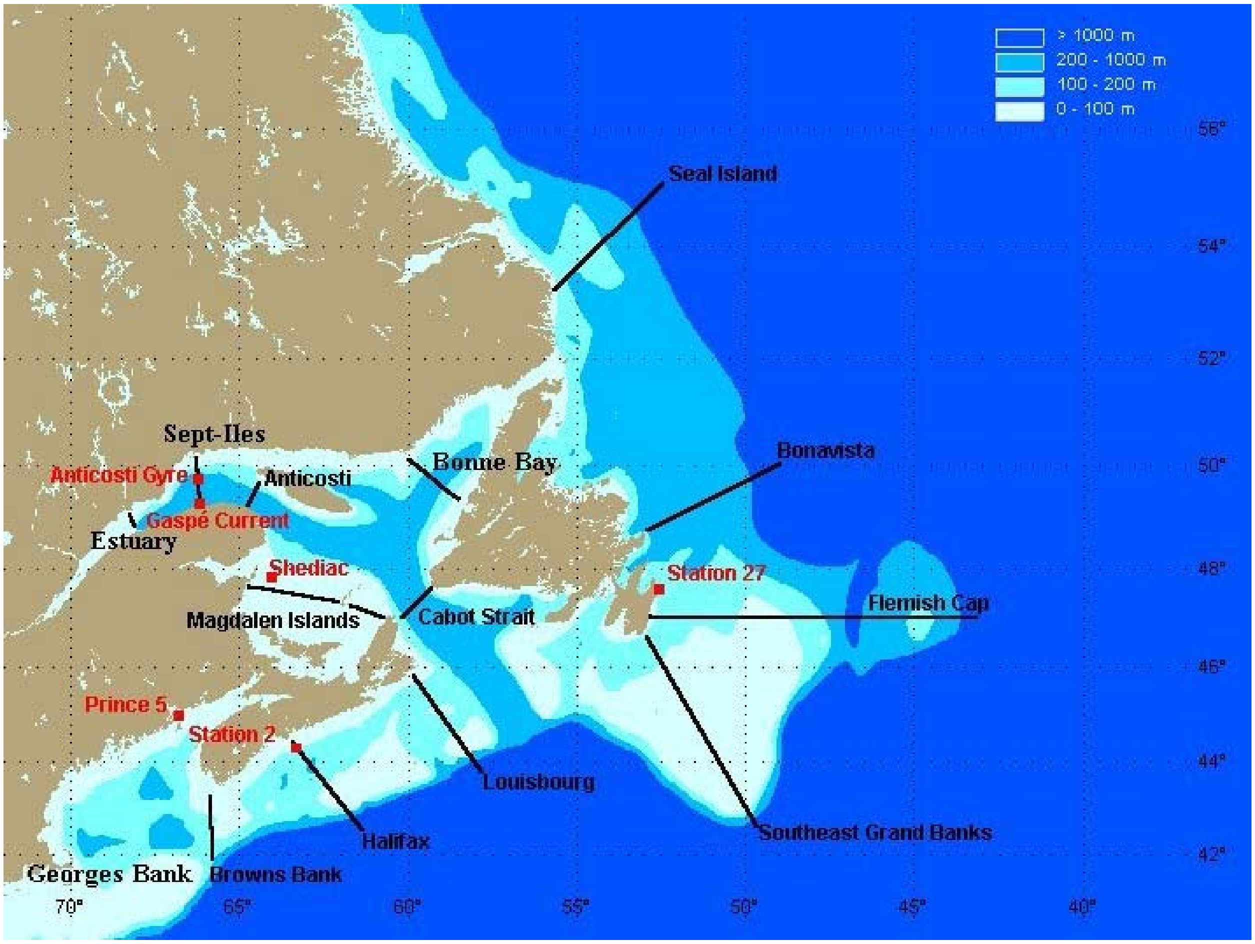

Figure 1. The network of fixed-stations (red squares) and cross-shelf transects (black lines) comprising the Northwest **A**ltantic **Z**onal **M**onitoring **P**rogram (AZMP).

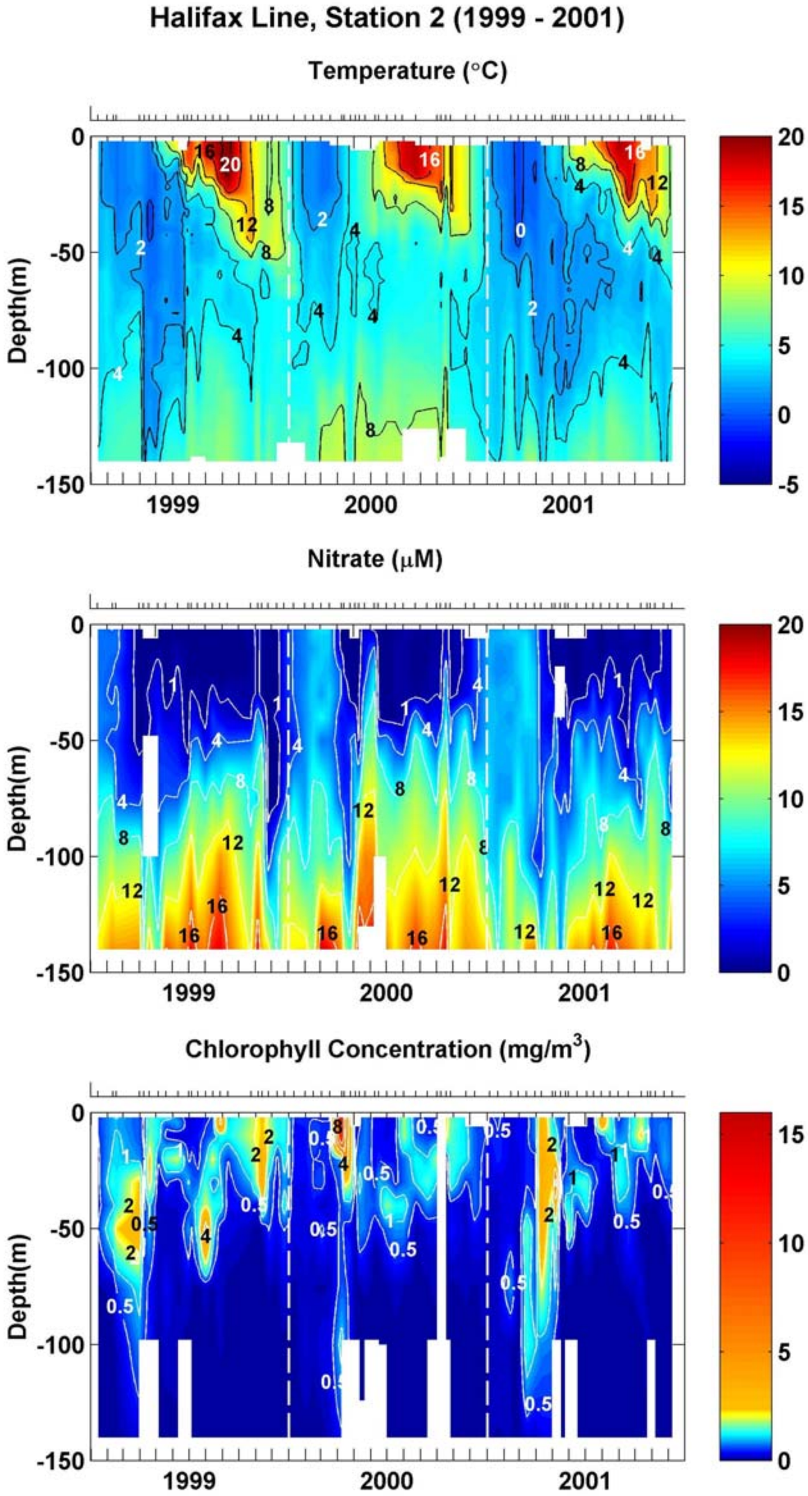

Figure 2. Time-series of temperature, nitrate and chlorophyll concentrations at the AZMP fixed-station off Halifax (Station 2, see Fig. 1 for location), 1999-2001. Full-depth samples were collected approximately twice monthly (sampling times indicated on scale above each panel). Vertical dashed lines indicate years-end.

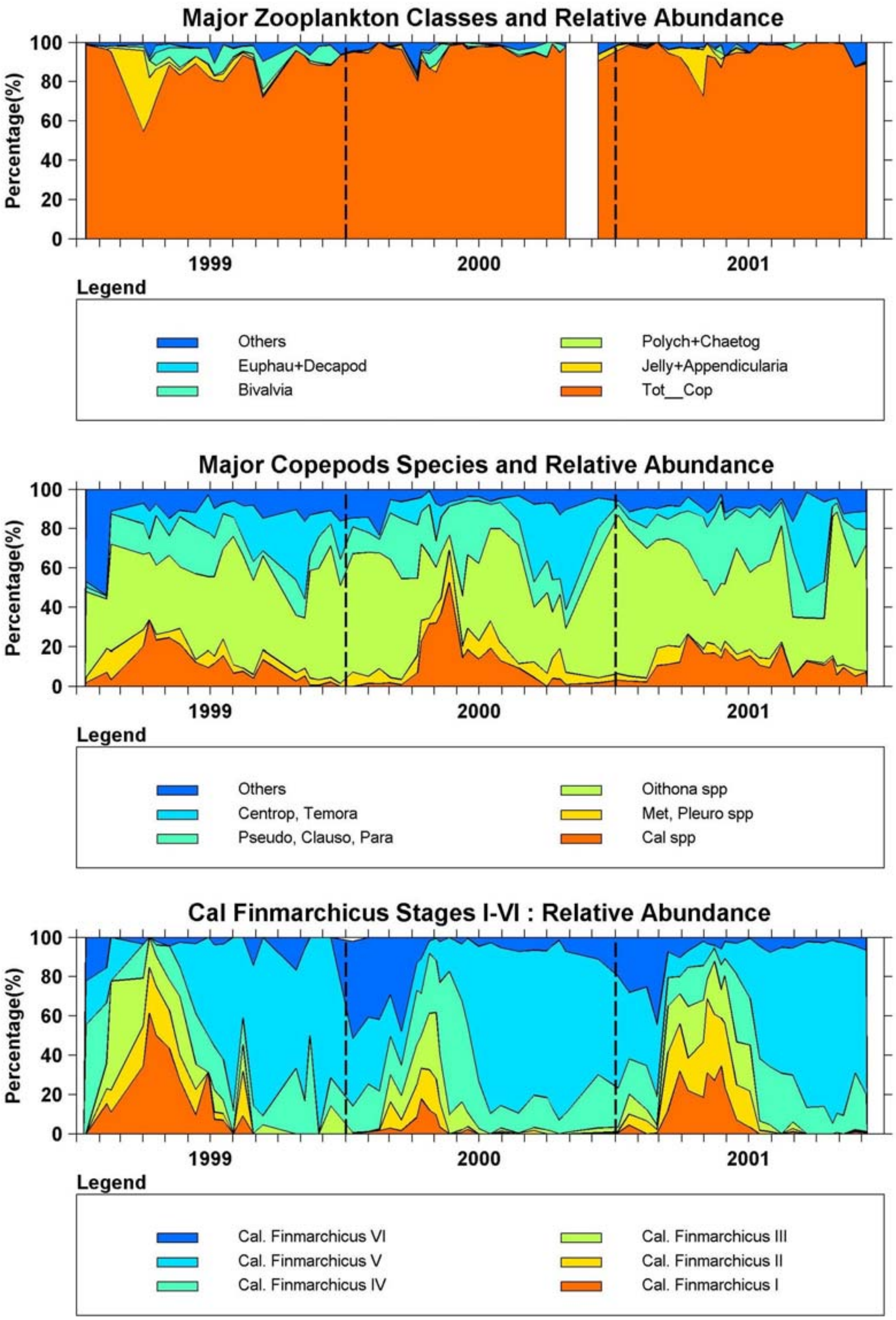

Figure 3. Time-series of zooplankton community structure at the AZMP fixed-station off Halifax, (Station 2, see Fig. 1 for location), 1999-2001. Top panel: relative numerical abundance (%) of major zooplankton classes, middle panel: relative abundance (%) of major copepod species, bottom panel: relative abundance (%) of *C. finmarchicus* developmental stages.

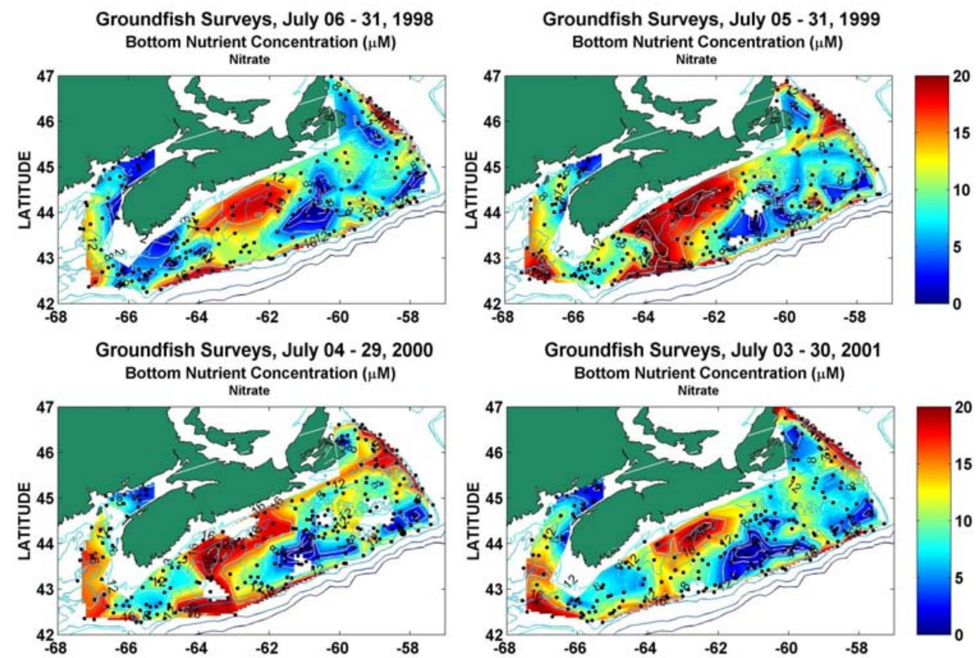

Figure 4. Bottom water nitrate concentrations in the eastern Gulf of Maine and on the Scotian Shelf during the annual summer groundfish surveys, 1998-2001. Black dots indicate station positions.

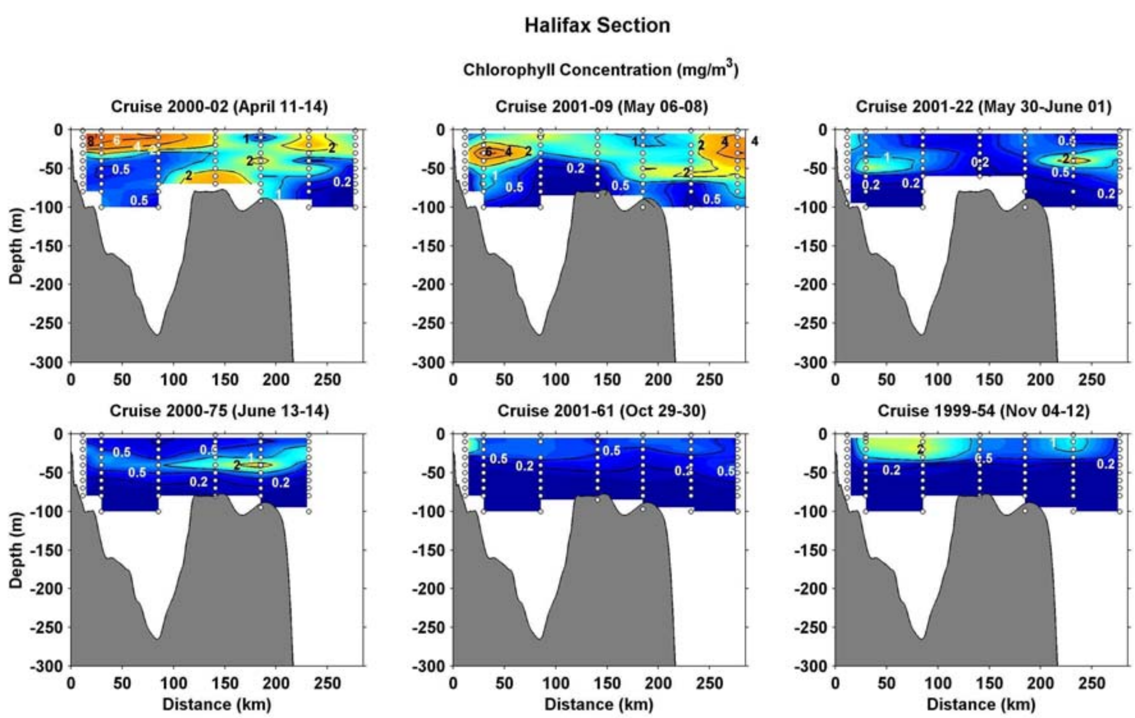

Figure 5. Seasonal (April – November) variability in chlorophyll a concentrations along the Halifax line (See Fig. 1 for location). White dots indicate station positions and sampling depths.

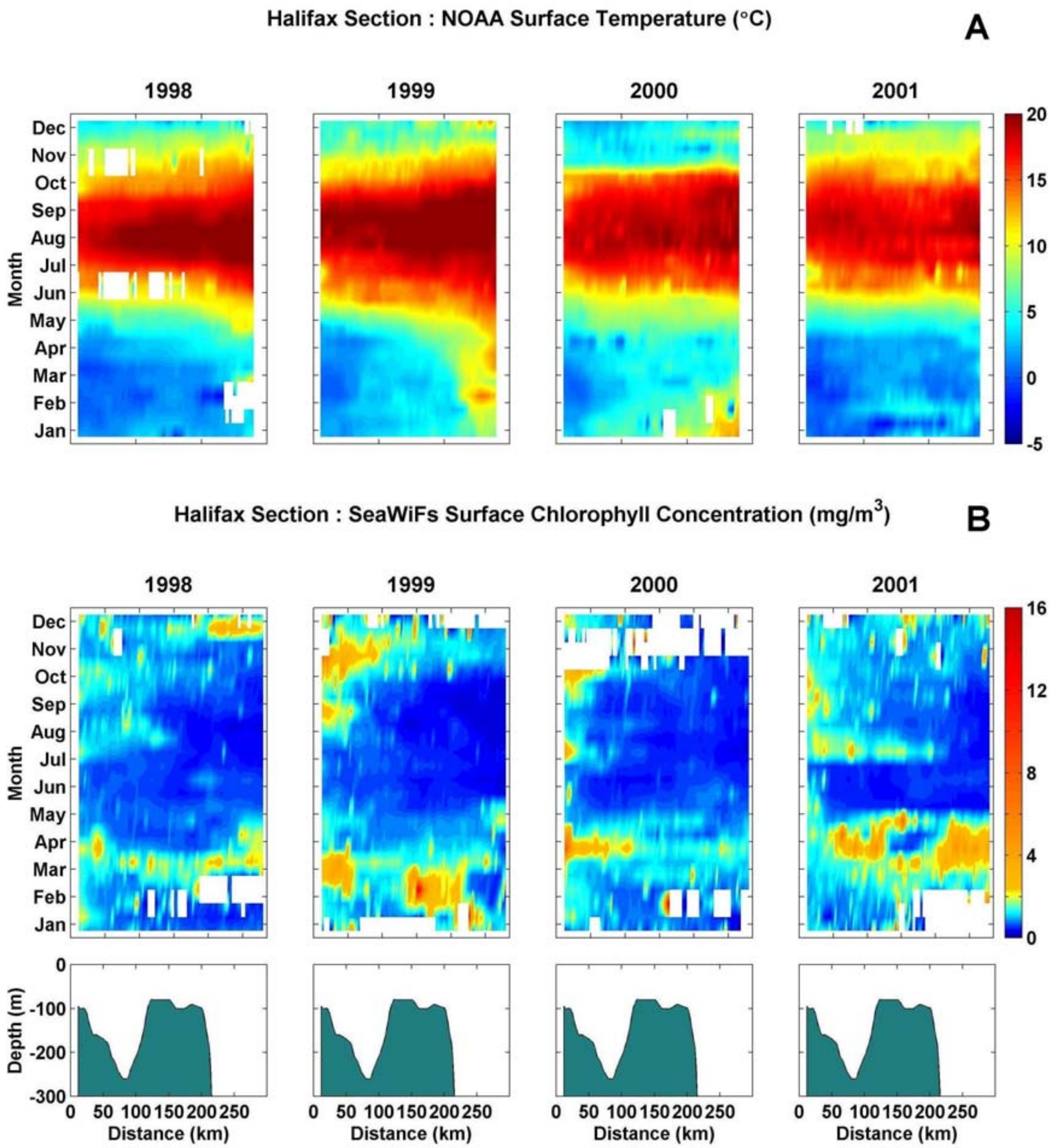

Figure 6. Variability of sea-surface temperature, SST (panel A) and surface chlorophyll (panel B) along the Halifax line, 1998-2001 derived from bi-weekly composite satellite images. Bottom panel shows bathymetry.

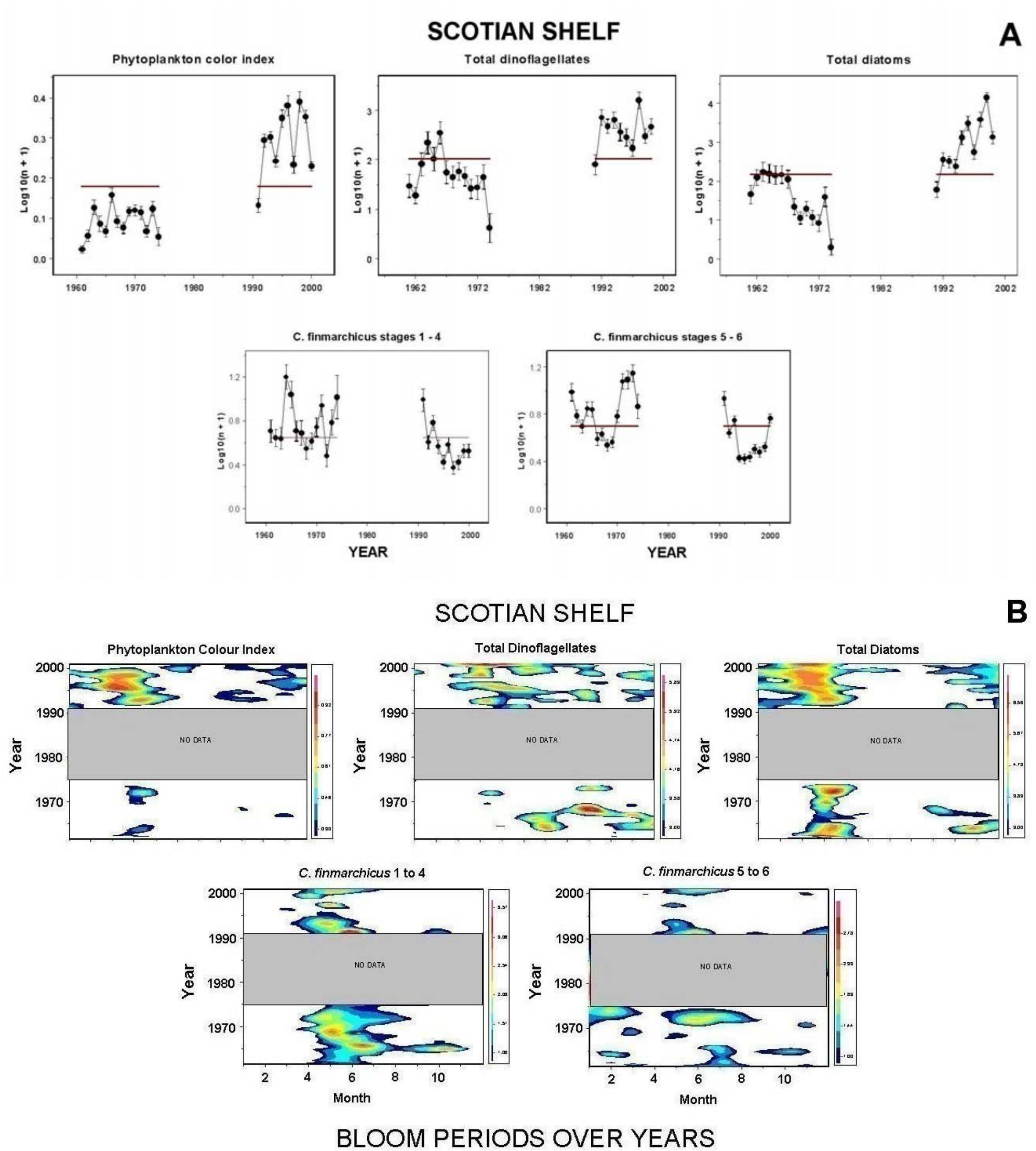

Figure 7. Annual means (panel A) and seasonal peaks (panel B) in phytoplankton biomass (colour index), diatom, dinoflagellate and *C. finmarchicus* abundances on the Scotian Shelf from CPR surveys, 1961-2000. Horizontal lines in upper panel are long-term means.

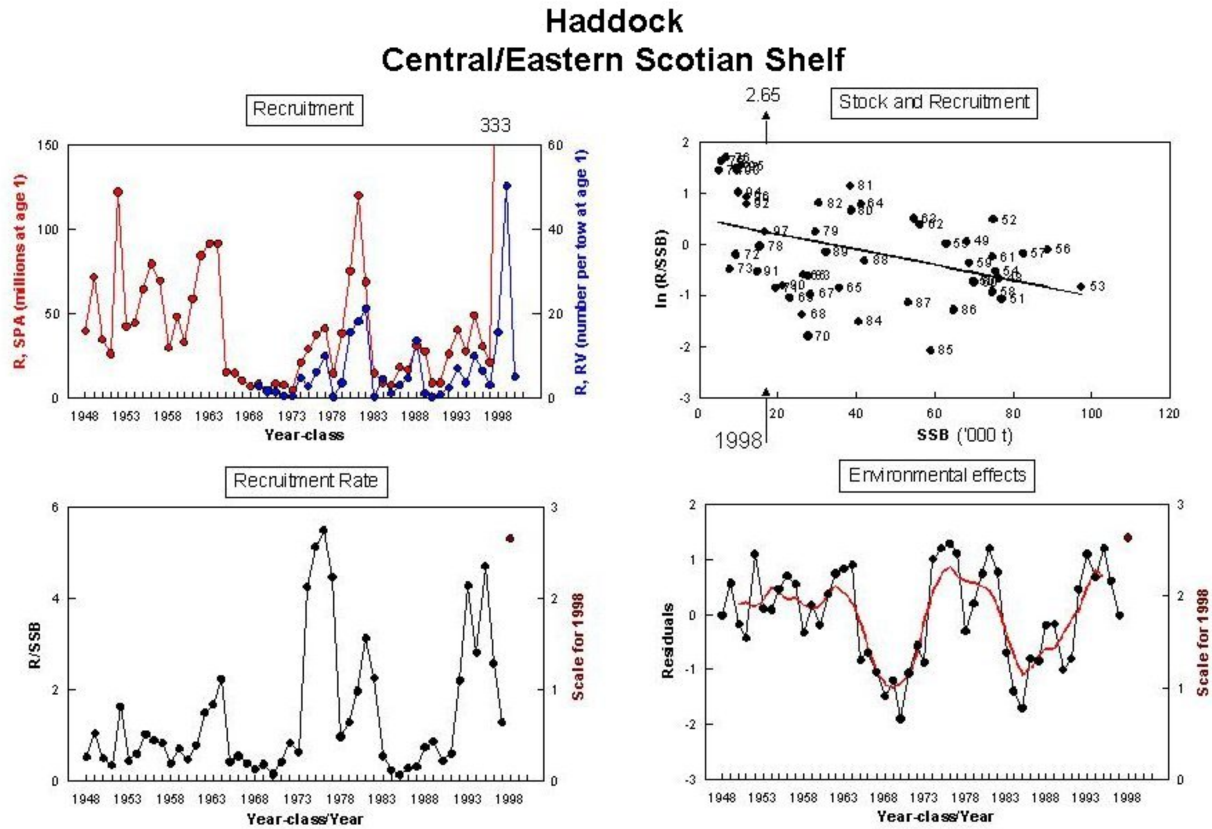

Figure 8. Recruitment indices for haddock on the Scotian Shelf. R = Recruitment; SPA = Sequential Population Analysis; RV = Research Vessel data; SSB = Spawning Stock Biomass.

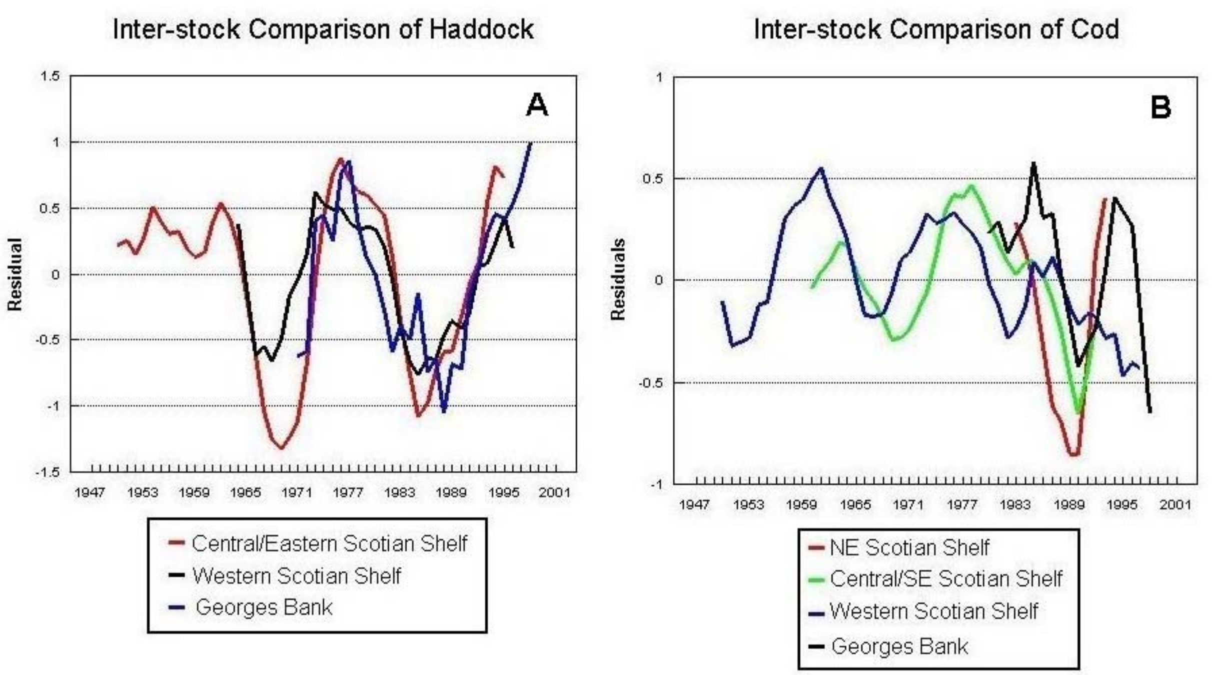

Figure 9. Inter-stock comparisons of stock—recruitment residuals for haddock (panel A) and cod (panel B) on the Scotian Shelf.