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ATLANTIC ZONE MONITORING PROGRAM

AZMP Bulletin PMZA

PROGRAMME DE MONITORAGE DE LA ZONE ATLANTIQUE

http://www.meds-sdmm.dfo-mpo.gc.ca/zmp/main_zmp_e.html

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Le Bulletin du PMZA

Le Bulletin annuel du PMZA publie des articles en anglais, français ou bilingues afin de fournir aux océanographes et aux chercheurs des pêches, aux gestionnaires de l'habitat et de l'environnement, ainsi qu'au public en général les plus récentes informations concernant le Programme de Monitorage de la Zone Atlantique (PMZA). Le bulletin présente une revue annuelle des conditions océanographiques générales pour la région nord-ouest de l'Atlantique, incluant le golfe du Saint-Laurent, ainsi que de l'information reliée au PMZA concernant des événements particuliers, des études ou des activités qui ont eu lieu au cours de l'année précédente.

The AZMP Bulletin

The AZMP annual Bulletin publishes English, French, and bilingual articles to provide oceanographers and fisheries scientists, habitat and environment managers, and the general public with the latest information concerning the Atlantic Zone Monitoring Program (AZMP). The Bulletin presents an annual review of the general oceanographic conditions in the Northwest Atlantic region, including the Gulf of St. Lawrence, as well as AZMP-related information concerning particular events, studies, or activities that took place during the previous year.

AZMP / PMZA

Fig. 1 Locations of sections and fixed stations.

Position des transects et des stations fixes.

The Atlantic Zone Monitoring Program

The AZMP was implemented in 1998 with the aim of collecting and analyzing the biological, chemical, and physical field data that are necessary to (1) characterize and understand the causes of oceanic variability at the seasonal, interannual, and decadal scales, (2) provide multidisciplinary data sets that can be used to establish relationships among the biological, chemical, and physical variables, and (3) provide adequate data to support the sound development of ocean activities. AZMP involves the Gulf, Québec, Maritimes, and Newfoundland regions of DFO. Its sampling strategy is based on (1) seasonal and opportunistic sampling along "sections" to quantify the oceanographic variability in the Canadian NW Atlantic shelf region, (2) higher-frequency temporal sampling at more accessible "fixed sites" to monitor the shorter time scale dynamics in representative areas, (3) fish survey and remote sensing data to provide broader spatial coverage and a context to interpret other data, and (4) data from other existing monitoring programs such as CPR (Continuous Plankton Recorder) lines, Sea Level Network, nearshore Long-Term Temperature Monitoring, Toxic Algae monitoring, or from other external organizations (e.g., winds and air temperatures from Environment Canada) to complement AZMP data.

The key element of the AZMP sampling strategy is the oceanographic sampling at fixed stations and along sections. The fixed stations are occupied about every two weeks, conditions permitting, and the sections are sampled from one to three times during the year. The location of the regular sections and the fixed stations are shown in Figure 1. Temperature, salinity, fluorescence, oxygen, chl *a*, nitrates, silicates, and phosphates are measured, and phytoplankton and zooplankton samples are collected. These measurements are carried out following well-established common protocols.

AZMP Personnel

A large number of scientists and technicians participate in the AZMP, either collecting, editing, processing, analyzing, or presenting the data. The following people have each played a significant role in the activities of the program; however, the list does not include all of the personnel who have contributed. For those not mentioned in the list, but who have helped during the past years, the AZMP is truly appreciative.

Gulf Region / Région du Golfe

Joël Chassé[1], Doug Swain[6]

Marine Environmental Data Service / Service des données sur le milieu marin

Savi Narayanan[3], Mathieu Ouellet[3,7], Cara Schock[3]

Maritimes Region / Région des Maritimes

Doug Gregory[3], Glen Harrison[2], Ross Henry[1], Mary Kennedy[3], Bill Li[2], Heidi Maass[4], Michel Mitchell[1], Kevin Pauley[2], Brian Petrie[1], Liam Petrie[8], Roger Pettipas[8], Doug Sameoto[2], Victor Soukhovtsev[8], Jeff Spry[2]

Le Programme de Monitorage de la Zone Atlantique

Le PMZA a été mis en œuvre en 1998 et vise à collecter et analyser l'information biologique, chimique et physique recueillie sur le terrain afin de (1) caractériser et comprendre les causes de la variabilité océanique aux échelles saisonnières, inter-annuelles et décadales, (2) fournir les ensembles de données pluridisciplinaires qui sont nécessaires pour établir des relations entre les variables biologiques, chimiques et physiques et (3) fournir les données pour le développement durable des activités océaniques. Le PMZA implique les régions du Golfe, du Québec, des Maritimes et de Terre-Neuve du MPO. Sa stratégie d'échantillonnage est fondée sur (1) l'échantillonnage saisonnier et opportuniste le long de «transects» afin de quantifier la variabilité biologique, chimique et physique de l'environnement, (2) l'échantillonnage à plus haute fréquence à des «stations fixes» plus accessibles pour monitorer la dynamique à plus fine échelle de temps dans des régions représentatives, (3) l'utilisation des données provenant des missions d'évaluation de stocks et de la télédétection pour fournir une couverture spatiale plus vaste et le contexte pour l'interprétation des autres données et (4) l'utilisation de données provenant d'autres programmes de monitorage comme les transects CPR («Continuous Plankton Recorder»), les réseaux côtiers de niveau d'eau et de température, le monitorage des algues toxiques, ou provenant d'autres organismes externes (ex. vents et température de l'air de Environnement Canada) pour complémenter les données du PMZA.

L'élément clé de la stratégie d'échantillonnage est la collecte de mesures océanographiques des stations fixes et le long de transects. Les stations fixes sont occupées à toutes les deux semaines, dépendant des conditions, et les sections sont échantillonnées de 1 à 3 fois durant l'année. La localisation des transects et des stations fixes est illustrée à la Figure 1. L'échantillonnage régulier comprend des mesures de température, salinité, fluorescence, oxygène, chl *a*, nitrates, silicates et phosphates, ainsi que la collecte d'échantillons de phytoplancton et de zooplancton. Ces mesures sont effectuées suivant des protocoles communs bien établis.

Personnel du PMZA

Un grand nombre de scientifiques et de techniciens participent au PMZA, soit à la collecte, l'édition, la réalisation, l'analyse ou la présentation des données. Les personnes suivantes ont joué un rôle significatif dans les activités du programme, mais la liste n'inclue pas tout le personnel qui a contribué. Pour ceux qui ne sont pas mentionnés dans la liste, nous aimerions leur exprimer notre gratitude pour l'aide précieuse qu'ils ont fournie au PMZA au cours des dernières années.

Newfoundland Region / Région de Terre-Neuve

Wade Bailey[1], Charlie Brombey[3], Eugene Colbourne[1], Joe Craig[1], Charles Fitzpatrick[1], Sandy Fraser[2], Daniel Lane[1], Gary Maillet[2], Pierre Pepin[2], Dave Senciall[3], Tim Shears[2], Paul Stead[1]

Québec Region / Région du Québec

Laure Devine[3], Marie-Lyne Dubé[5], Alain Gagné[5], Yves Gagnon[5], Peter Galbraith[1], Denis Gilbert[1], Michel Harvey[2], Pierre Joly[2], Caroline Lafleur[3], Pierre Larouche[4], Bernard Pelchat[3], Bernard Pettigrew[1], Liliane St-Amand[2], Jean-François St-Pierre[2], Michel Starr[2], Jean-Claude Therriault[2]

[1]Physical Oceanography / Océanographie physique; [2] Biological Oceanography / Océanographie biologique; [3] Data Management / Gestion des données; [4] Remote Sensing / Télédétection; [5] Sampling & laboratory analyses / Échantillonnage & analyses en laboratoire; [6] Fish Surveys / Missions d'évaluation de poissons; [7]Webmaster / Webmestre; [8]Graphic & Data Analyst / Graphiste & analyste de données.

Physical and Biological Status of the Environment

État de l'environnement physique et biologique

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Physical Environment

A satellite image from early spring 2003 shows a vast area of cold surface water over the Labrador and Newfoundland shelf, Gulf of St. Lawrence and eastern Scotian Shelf (Fig. 1). The offshore branch of the Labrador Current, which is the dominant flow on the Canadian east coast, is clearly visible on the edge of the Grand Banks; the inshore branch is seen in Avalon Channel. However, temperatures were only about 1˚C colder than normal in the Gulf of St. Lawrence and on the Newfoundland Shelf and about 2˚C colder than normal on the Scotian Shelf. For the entire year, temperatures were generally warmer than normal on the Newfoundland Shelf and colder than normal in the Gulf while there was a mixture of cold and warm conditions on the Scotian Shelf.

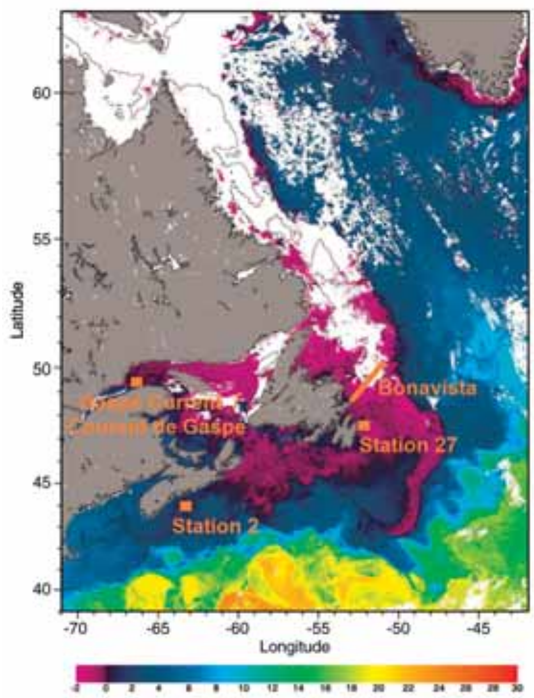

Fig. 1 Sea-surface temperature, spring 2003. The locations of fixed stations (squares) and the Bonavista section (line) discussed in the article are shown. White areas indicate sea-ice or clouds.

Température de surface de la mer au printemps 2003. Les positions des stations fixes (carrés) et du transect Bonavista (ligne) qui sont discutées dans cet article sont indiquées. Les régions blanches représentent de la glace à la surface de la mer ou des nuages.

Air temperatures are an indication of the amount of heat that can be transferred from the atmosphere into the ocean. During 2003, they varied systematically over the region, typically 1-2˚C colder than normal from January to May and

Environnement physique

Une image satellitaire de début du printemps 2003 montre une vaste région d'eau de surface froide couvrant le plateau de Terre-Neuve et du Labrador, le golfe du Saint-Laurent et la partie est du plateau Néo-Écossais (Fig. 1). La branche plus au large du courant du Labrador, qui représente le flux dominant sur la côte est canadienne, est nettement visible à la périphérie des Grands Bancs; la branche plus côtière du courant passe par le chenal Avalon. Cependant, les températures sont seulement environ 1 ˚C plus froide que la normale dans le golfe du Saint-Laurent et sur le plateau de Terre-Neuve, et environ 2 ˚C plus froide que la normale sur le plateau Néo-Écossais. Globalement pour l'année, les températures étaient généralement plus chaudes que la normale sur le plateau de Terre-Neuve et plus froide que la normale dans le Golfe, tandis qu'il y avait un mélange de conditions d'eaux froides et chaudes sur le plateau Néo-Écossais.

La température de l'air est une indication de la quantité de chaleur qui peut être transférée de l'atmosphère vers l'océan. Systèmatiquement, en 2003, la température au dessus de toute la région a été de 1 à 2 ˚C plus froide que la normale entre janvier et mai, et de 1 à 3 ˚C plus chaude que la normale entre juin et décembre (Fig. 2).

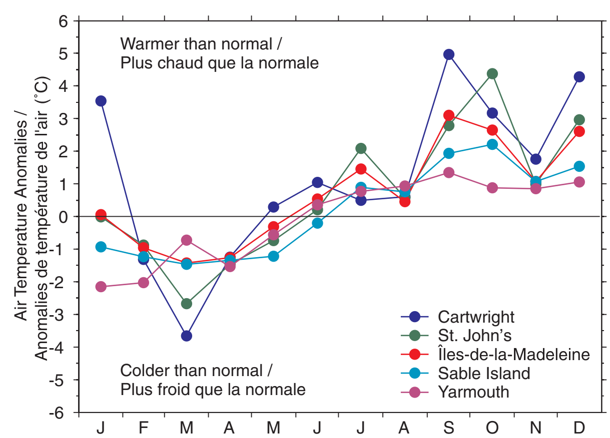

Fig. 2 Differences in the monthly air temperatures in 2003 compared to the 1971-2000 average values for Cartwright, Labrador; St. John's, Newfoundland; Îles-de-la-Madeleine, Québec; and Sable Island and Yarmouth, Nova Scotia.

Différences de températures de l'air mensuelles en 2003 comparées aux valeurs moyennes 1971-2000 pour Cartwright au Labrador, St. John's Terre-Neuve, Îles-de-la-Madeleine au Québec, et Sable Island et Yarmouth en Nouvelle-Écosse.

about 1-3˚C warmer than normal from June to December (Fig. 2).

Station 27, the Gaspé Current station, and Halifax Station 2 fixed stations are the focus of the discussion of physical and biological oceanic variability. Data from other sites are presented in the research documents and environmental status reports available on the CSAS website (http://www.dfo-mpo.gc.ca/csas/).

Water temperature cooled almost uniformly with depth at Station 27 off St. John's during the winter to less than -1˚C by the end of March (Fig. 3). Sub-zero temperatures persisted at depth during 2003. A shallow warm layer developed during spring and summer and reached maximum values of about 13˚C in August. Temperatures were about 1˚C colder than normal from 25-150 m in October; they were about 1˚C warmer than normal from 0-60 m in July and August.

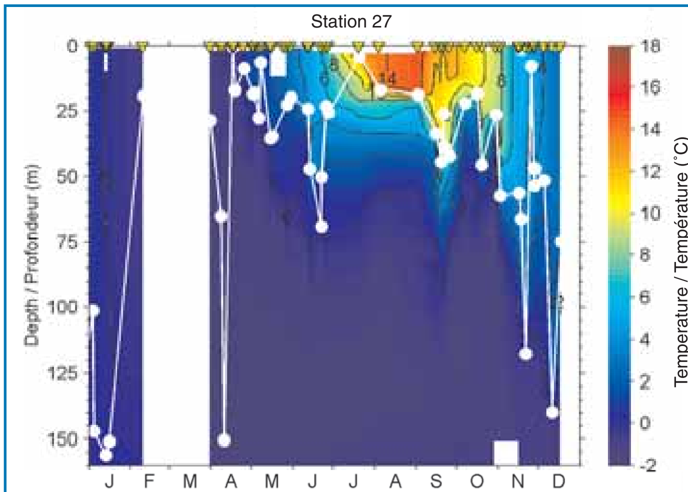

Fig. 3 Temperature profile in 2003 for Station 27 off St. John's Newfoundland. The thick white line shows the depth of the mixed layer, derived from the density profiles. The large gap in the figure is a period when no data were collected.

Profil de température en 2003 pour la Station 27 au large de St. John's Terre-Neuve. La ligne blanche épaisse indique la profondeur de la couche de mélange, dérivée des profils de densité. La zone blanche à la gauche de la figure indique une absence de données.

In early March at the Gaspé Current station, temperatures were below 0˚C from 0 to 80 m (Fig. 4). The surface mixed layer was only 20 m deep due to low salinities (about 31.3) in the top 15 m overlaying saltier (about 32.45), near-freezing waters from 45 to 70 m. Near-surface temperatures increased to a maximum of 14.1°C by mid August. Surface salinities were generally above normal due to much lower than normal freshwater inflow from the St. Lawrence River.

The outstanding feature at Halifax Station 2 was the extensive cold layer that developed during the winter and persisted at depth through 2003 (Fig. 5). Temperatures were typically 2˚C colder than normal. The mixed layer depth—the layer extending from the surface with nearly uniform properties—was deeper than normal throughout most of 2003. This was especially true from February to April, when it was about 20 m deeper than average.

Time series of the cold intermediate layer (CIL, temperature ≤ 0˚C) area from the Bonavista section, Newfoundland, as

La Station 27, la station du courant de Gaspé et la Station 2 de Halifax sont au cœur de notre discussion présente sur la variabilité océanique biologique et physique. Les données pour les autres stations fixes sont présentées dans les documents de recherche et les rapports sur l'état de l'environnement présentés sur le site web du SCCS (http://www.dfo-mpo.gc.ca/csas/).

À la Station 27 au large de St. John's, la masse d'eau s'est graduellement refroidie presque uniformément sur toute la colonne d'eau au cours de l'hiver pour atteindre une température de -1 ˚C vers la fin mars (Fig. 3). Les températures sous zéro ont persisté en profondeur au cours de toute l'année 2003. Une mince couche de surface plus chaude s'est développée au printemps et à l'été, pour atteindre une température maximale d'environ 13 ˚C en août. La température de l'eau était environ 1 ˚C plus froide que la normale dans la couche de 25-150 m en octobre; elle était environ 1 ˚C plus chaude que la normale dans la couche de 0-60 m en juillet et août.

Au début de mars, à la station du courant de Gaspé, la température atteignait moins de 0 ˚C dans la couche de 0-80 m (Fig. 4). La couche de surface mélangée avait seulement 20 m de profondeur en raison des faibles salinités (environ 31.30) dans les premiers 15 m qui recouvraient une couche plus salée (environ 32.45) s'étendant de 45 à 70 m et qui était caractérisée par des températures près du point de congélation. La température des eaux de surface a ensuite graduellement augmenté jusqu'à un maximum de 14.1 °C vers la mi-août. La salinité de surface était généralement au-dessus de la normale en raison des apports d'eaux douces du fleuve Saint-Laurent qui ont été beaucoup plus faibles que la normale.

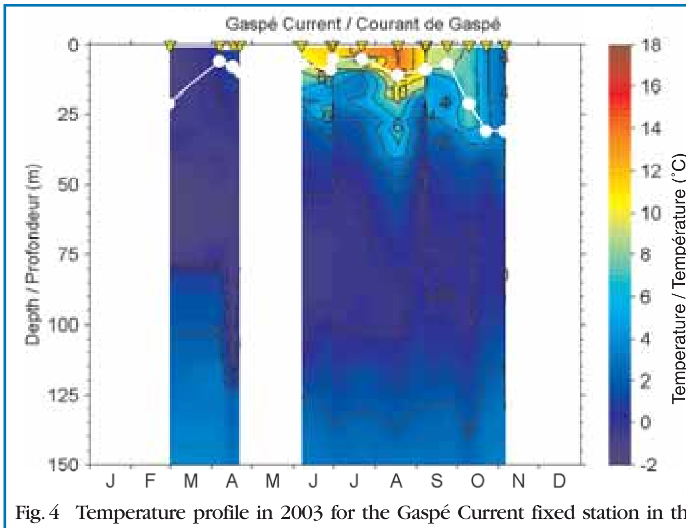

Fig. 4 Temperature profile in 2003 for the Gaspé Current fixed station in the Gulf of St. Lawrence. The thick white line shows the depth of the mixed layer, derived from the density profiles. White areas are data gaps.

Profil de température en 2003 pour la station du courant de Gaspé dans le golfe du Saint-Laurent. La ligne blanche épaisse indique la profondeur de la couche de mélange, dérivée des profils de densité. Les zones blanches indiquent une absence de données.

Le fait saillant à la Station 2 de Halifax était la couche froide extensive qui s'est développée durant l'hiver et qui a persisté en profondeur tout au long de l'année 2003 (Fig. 5). La température était typiquement 2 ˚C plus froide que la normale. La couche de mélange près de la surface, avec des propriétés presque uniformes, était plus profonde que la normale durant toute l'année 2003. Ceci est particulièrement vrai à partir de

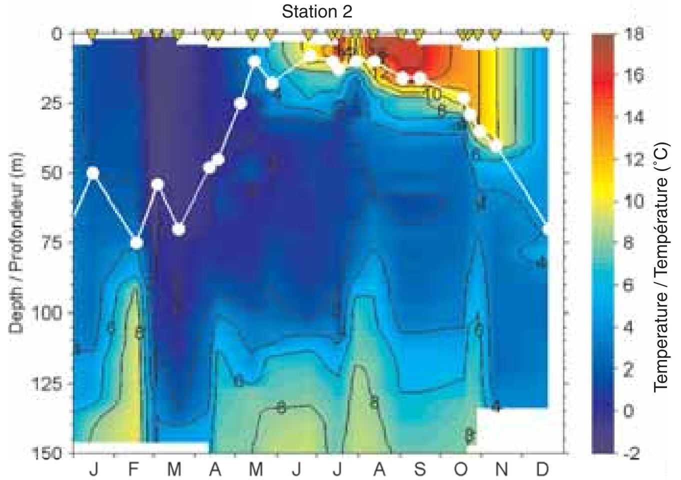

Fig. 5 Temperature profile in 2003 at Halifax Station 2. The thick white line shows the depth of the mixed layer, derived from the density profiles.

Profil de température en 2003 pour la Station 2 de Halifax. La ligne blanche épaisse indique la profondeur de la couche de mélange, dérivée des profils de densité.

well as the volume of the CIL in the Gulf of St. Lawrence and of shelf water (water mass analysis) on the Scotian Shelf can vary substantially from year to year (Fig. 6). In 2003, the area of the CIL on the Bonavista section was slightly below the long-term mean, indicating warmer than normal conditions and agreeing with the observations at Station 27. On the other hand, the CIL volume in the Gulf of St. Lawrence was greater than the long-term mean, indicating a colder than normal year. A similar situation was found on the Scotian Shelf, where the amount of cold, fresh shelf water was among the greatest on record.

Chemical and Biological Environment

At Station 27, the onset of the spring phytoplankton bloom (Fig. 7A) occurred about two weeks later than the long-term average, although the duration (~30-40 days) and overall bio-

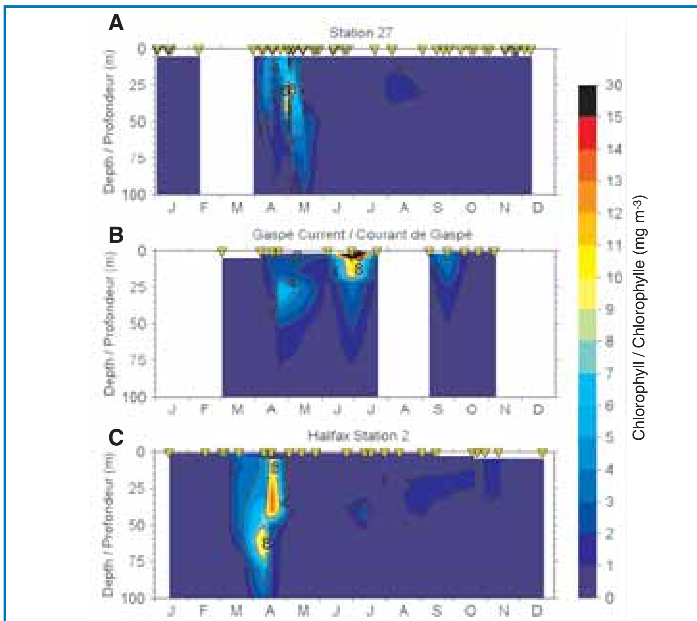

Fig. 7 Phytoplankton chlorophyll concentration for the fixed stations: (A) Station 27, (B) Gaspé Current station and (C) Halifax Station 2.

Concentrations en chlorophylle du phytoplancton pour les stations fixes : (A) Station 27, (B) station du courant de Gaspé et (C) Station 2 de Halifax.

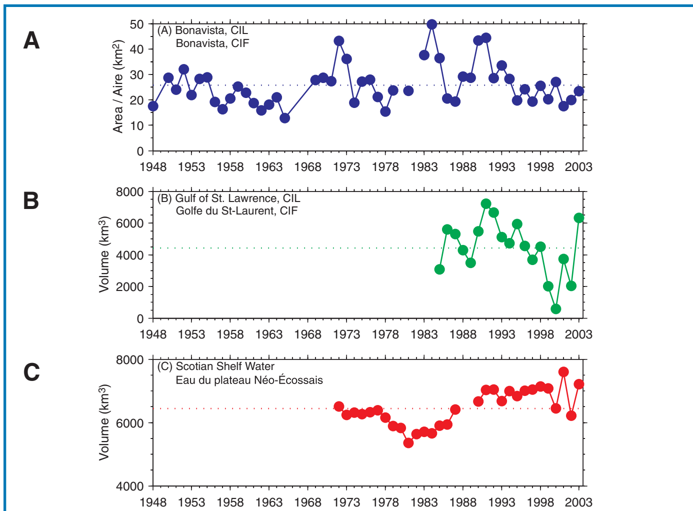

Fig. 6 Time series of (A) the CIL area on the Bonavista section, (B) CIL volume in the Gulf of St. Lawrence and (C) shelf water volume on the Scotian Shelf. Horizontal lines are the means of all points in each plot.

Séries temporelles (A) de l'aire occupée par la CIF le long du transect de Bonavista, (B) du volume de la CIF dans le golfe du Saint-Laurent et (C) du volume d'eau du plateau Néo-Écossais. Les lignes horizontales représentent la moyenne de tous les points pour chaque graphique.

février jusqu'à avril où on observe une couche de mélange plus profonde d'environ 20 m que la moyenne.

La série temporelle de l'aire couverte par la couche intermédiaire froide (CIF, avec des températures ≤ 0 ˚C) le long du transect de Bonavista à Terre-Neuve, aussi bien que le volume de la CIF dans le golfe du Saint-Laurent et celui de la masse d'eau (selon une analyse statistique) du plateau Néo-Écossais montrent des variations interannuelles significatives (Fig. 6). En 2003, l'aire couverte par la CIF sur le transect de Bonavista était légèrement sous la moyenne à long terme, indiquant des conditions plus chaudes que la normale, en accord avec les observations à la Station 27. D'un autre côté, le volume de la CIF dans le golfe du Saint-Laurent était plus grand que la moyenne à long terme, indiquant une année plus froide que la normale. Une situation similaire a été observée sur le plateau Néo-Écossais, où la quantité d'eaux froides et moins salées sur le plateau était parmi les plus élevée dans les annales.

Environnement chimique et biologique

À la Station 27, le début de la floraison du phytoplancton (Fig. 7A) se produit environ deux semaines plus tard que la moyenne à long terme, même si sa durée (~30-40 jours) et sa biomasse globale n'étaient pas différentes de leurs moyennes à long terme. Le délais du début de la période de floraison printanière a probablement été causé par un mélange plus intense de la colonne d'eau durant l'hiver et au début du printemps en comparaison à l'année 2002.

En 2003, l'initiation de la floraison principale du phytoplancton à la station du courant de Gaspé s'est produite en mai (Fig. 7B), un mois plus tôt que d'habitude, probablement en raison des débits d'eau douce qui étaient sous de la normale. La biomasse moyenne du phytoplancton était aussi plus élevée qu'au cours des trois années précédentes. Pour la troisième année consécutive, l'analyse taxonomique de la communauté phytoplanctonique en 2003 a révélé la présence significative de la diatomée *Neodenticula seminae* qui origine vraisemblablement de l'océan Pacifique.

mass were not different from the long-term mean. The delay in the onset of the spring bloom may have been due to stronger mixing of the water column during winter and early spring relative to 2002.

In 2003, the initiation of the major phytoplankton bloom at the Gaspé Current station occurred in May (Fig.7B), one month earlier than usual, probably due to the below-normal spring freshwater runoff. The average phytoplankton biomass was also higher than in the previous three years. For a third consecutive year, the analysis of the phytoplankton community composition in 2003 revealed the presence of the diatom *Neodenticula seminae*, probably originating from the Pacific Ocean.

A pronounced spring bloom was also seen off Halifax in 2003 (Fig. 7C); chlorophyll levels were the highest and the bloom persisted longer than any observed in the five-year AZMP record, possibly due to the high inventories of nutrients during the previous winter.

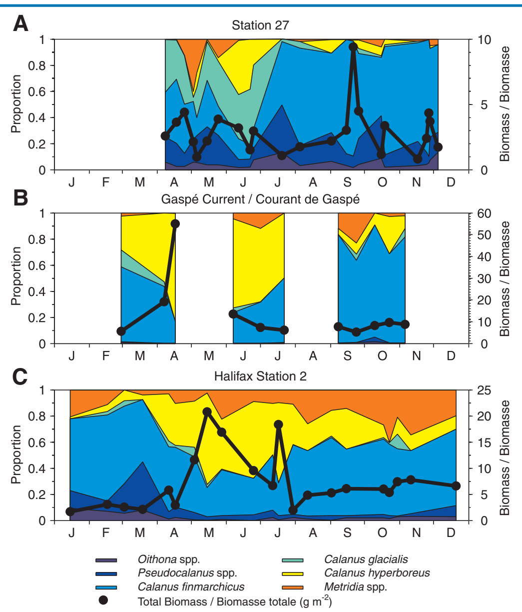

Fig. 8 Relative importance of the dominant copepod species for the fixed stations: (A) Station 27, (B) Gaspé Current, and (C) Halifax Station 2. The solid line shows the estimated integrated biomass of copepods (surface-bottom).

Importance relative de quelques espèces dominantes de copépodes pour les stations fixes : (A) Station 27, (B) station du courant de Gaspé et (C) Station 2 de Halifax. La ligne noire épaisse indique la biomasse intégrée de copépodes (surface-fond).

Large calanoid copepods make up the bulk of the biomass at the three fixed stations, but smaller species (*Pseudocalanus* sp. and *Oithona* spp.) represent ~20% of the biomass at Station 27 while deep-water species (*Metridia* spp. and *Calanus hyperboreus*) are a significant part of the biomass in the Gaspé Current and off Halifax (Fig. 8). At all sites, *Calanus finmarchicus* is a key species.

The beginning of the reproduction cycle of *C. finmarchicus* off St. John's was delayed by approximately one month, consistent with the delay in the spring phytoplankton bloom, and its late-summer abundance was greater than in the previous

Une floraison printanière de phytoplancton prononcée a aussi été observée au large de Halifax en 2003 (Fig. 7C); les niveaux de chlorophylle atteints étaient les plus élevés et la floraison a persisté plus longtemps que tout ce qui a été observé au cours des cinq ans d'existence du PMZA, probablement attribuable au pool très élevé en sels nutritifs qui était présent à la fin de l'hiver précédent.

Les gros copépodes de type calanoides forment la majeure partie de la biomasse aux trois stations fixes mais les plus petites espèces comme *Pseudocalanus* sp. and *Oithona* spp. représentent 20 % de la biomasse à la Station 27, tandis que les espèces d'eau profonde comme *Metridia* spp. and *Calanus hyperboreus* représentent une partie significative de la biomasse dans le courant de Gaspé et au large de Halifax (Fig. 8). À toutes les stations, *Calanus finmarchicus* représente une espèce clé.

Le début du cycle de reproduction de *C. finmarchicus* est retardé d'environ un mois à la Station 27, ce qui est cohérent avec le délais observé dans la floraison printanière du phytoplancton, et leur abondance de fin d'été était plus grande qu'au cours des cinq dernières années. L'augmentation graduelle

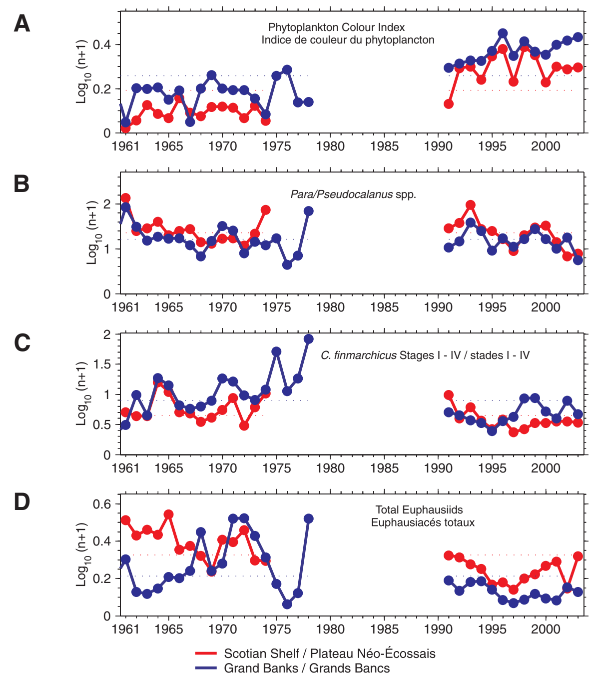

Fig. 9 Data from the Continuous Plankton Recorder (CPR): annual phytoplankton colour index (A) and annual average abundances of dominant zooplankton taxa (B, C, D) from the Scotian Shelf (red) and Grand Banks (blue) regions.

Données CPR (« Continuous Plankton Recorder ») : l'indice annuel de coloration du phytoplanction (A) et les abondances annuelles moyennes de certains taxons dominants du zooplancton (B, C, D) pour les régions du plateau Néo-Écossais (rouge) et des Grands Bancs (bleu).

d'abondance et la présence d'espèces de copépodes normalement associées avec des eaux froides (*C. glacialis*, *C. hyperboreus*) qui ont été observées à la Station 27 depuis 1999 s'est renversée vers les espèces d'eaux plus chaudes en 2003.

La biomasse zooplanctonique à la station du courant de Gaspé était légèrement plus élevée qu'au cours des trois années précédentes. La proportion relative de copépodes dans la communauté zooplanctonique a augmenté de 70 à 95 % entre 1999 et 2003. Le cycle de reproduction de *C. finmarchicus* était simifive years. The gradual increase of abundance and occurrence of copepod species normally associated with cold water (*C. glacialis*, *C. hyperboreus*) that had occurred at Station 27 since 1999 shifted back toward warm-water species in 2003.

The zooplankton biomass at the Gaspé Current station was slightly higher than in the previous three years. The relative proportion of zooplankton consisting of copepods increased from 70 to 95% from 1999 to 2003. The reproductive cycle of *C. finmarchicus* was similar to previous years, but the 2003 abundance was the highest since 1999.

Calanus finmarchicus abundance off Halifax was higher in 2003 than in 2002 and reversed the downward trend seen in the previous three years. The timing of reproduction off Halifax may have started somewhat later in 2003 (and persisted longer) than in 2002 based on the appearance of young stages.

Time series from the Continuous Plankton Recorder showed that phytoplankton abundance, as estimated by the phytoplankton colour index, was well above levels observed in the 1960s and 1970s on both the Grand Banks and the Scotian Shelf (Fig. 9A). On the other hand, zooplankton (*Para- / Pseudocalanus* spp., *C. finmarchicus*, total euphausiids), particularly the larger species (*C. finmarchicus* and euphausiids) which make up the bulk of the biomass, were generally less abundant during the 1990s and early 2000s relative to the early part of the time series in both regions (Fig. 9B, C, D).

Highlight 2003

The very cold February to April air and water temperatures that prevailed from Labrador to the Scotian Shelf are the climate highlight of 2003. This extreme cold event was accompanied by the largest inflow of cold salty (S > 32.35) waters through the Strait of Belle Isle into the Gulf of St. Lawrence (9-year record), the largest export of sea ice from the Gulf of St. Lawrence to the Scotian Shelf through Cabot Strait (41-year record), and the largest CIL volume on the Scotian Shelf (33-year record). A much thicker and colder than normal CIL was also observed in the Gulf of St. Lawrence and over the Grand Banks and Scotian Shelf. In the eastern Newfoundland inshore area of Smith Sound, near-record low temperatures in April caused the largest known mass mortality of Atlantic cod (see Colbourne et al., p. 45, in AZMP Bulletin no. 3).

While local air temperatures and winds play the major role in the annual cycle of water temperatures throughout the region, Canadian east coast waters are also strongly influenced by flow from the Arctic. Currents from the north bring not only cold water but also northern species of plankton. For example, coinciding with the high phytoplankton biomasses observed in the lower Estuary and the Gulf of St. Lawrence in 2003, we have observed the highest abundances of the cold-water copepod *Calanus finmarchicus* since 1999. The abundance of the arctic hyperiid amphipod *Themisto libellula*, which has been observed in the Gulf since the early 1990s, also increased significantly, from 0.17 individuals·m^{-2} in 2000 to 13 individuals· m^{-2} in 2003. This has been attributed to a significant increased inflow of cold Labrador Shelf water to the Gulf of St. Lawrence via the Strait of Belle Isle.

laire aux années précédentes mais leur abondance relative en 2003 était la plus élevée depuis 1999.

L'abondance de *Calanus finmarchicus* au large de Halifax était plus élevée en 2003 qu'en 2002, renversant la tendance à la baisse observée au cours des trois dernières années. En se basant sur le moment d'apparition des jeunes stades, le début du cycle de reproduction au large de Halifax a débuté un peu plus tard et a persisté plus longtemps en 2003 qu'en 2002.

Les séries temporelles de données CPR (« Continuous Plankton Recorder ») montrent que l'abondance du phytoplancton, déterminée par un indice de coloration, était bien au dessus des niveaux observés pendant les décennies 60 et 70 autant sur les Grands Bancs que sur le plateau Néo-Écossais (Fig. 9A). D'un autre côté, le zooplancton (*Para- /Pseudocalanus* spp., *C. finmarchicus* et les euphausides totaux), particulièrement les grosses espèces (*C. finmarchicus* et les euphausides) qui forment la majeure partie de la biomasse, était généralement moins abondant durant les années 1990 et le début des années 2000 en comparaison avec la première partie de la série temporelle dans les deux régions (Fig. 9B, C, D).

Faits saillants en 2003

Les températures très froides de l'air et de l'eau qui ont prévalu sur les plateaux du Labrador et de la Nouvelle-Écosse pour la période de février à avril représentent certainement l'événement climatique saillant de 2003. Cet événement de froid extrême a été accompagné du plus grand influx d'eaux froides et salées (S > 32.35) dans le golfe du Saint-Laurent via le détroit de Belle Isle (9 ans d'observations), de la plus grande exportation de glace de mer provenant du golfe du Saint-Laurent sur le plateau Néo-Écossais via le détroit de Cabot (41 ans d'observations), et du plus grand volume observé de la CIF sur le plateau Néo-Écossais (33 ans d'observations). Une CIF beaucoup plus épaisse et froide que la normale a aussi été observée dans le golfe du Saint-Laurent ainsi que sur les eaux recouvrant les régions des Grands Bancs et du plateau Néo-Écossais. Dans la région côtière de Smith Sound à l'est de Terre-Neuve, des températures près des records de froid en avril ont causé la plus grande mortalité massive de morue Atlantique que l'on ait jamais connue (voir Colbourne et al., p. 45, Bulletin No. 3 du PMZA).

Quoique la température locale de l'air et le vent jouent un rôle majeur dans le cycle annuel de la température de l'eau dans toute cette région, les eaux de la côte est du Canada sont aussi fortement influencées par les influx d'eaux provenant de l'Arctique. Les courants provenant du nord amènent non seulement des eaux froides mais aussi des espèces nordiques de plancton. Par exemple, coïncidant avec les fortes biomasses de phytoplancton observées dans l'estuaire maritime et le golfe du Saint-Laurent en 2003, on a observé les plus hauts niveaux d'abondance du copépode d'eau froide *Calanus finmarchicus* depuis 1999. L'abondance de l'espèce arctique d'amphipode *Themisto libellula*, qui est observée dans le Golfe depuis le début des années 1990, a aussi augmenté significativement, passant de 0.17 individus·m^{-2} en 2000, à 13 individus·m^{-2} en 2003. Ces augmentations sont attribuées à la recrudescence des influx d'eaux froides provenant du plateau du Labrador dans le golfe du Saint-Laurent via le détroit de Belle Isle.

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Summary of the Five-Year Review of the Atlantic Zone Monitoring Program

Sommaire de la revue de cinq ans du Programme de Monitorage de la Zone Atlantique

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During the development of the Atlantic Zone Monitoring Program (AZMP), Therriault et al. (1998) foresaw that a periodic audit of the program's progress was a key element for ensuring the best possible use of the scientific and operational resources dedicated to the continued assessment of oceanographic conditions on the East Coast of Canada. To this end, AZMP members, along with scientists from the Fisheries Oceanography Committee and from other client groups, identified a series of objective criteria to (1) assess the AZMP's progress in implementing the goals set out in the original proposal (Therriault et al. 1998), (2) identify strengths and limitations in the data collection and interpretation, and (3) map out tasks needed to make the program more effective. This article provides a summary of the major conclusions arising from the first 5-year review of the Atlantic Zone Monitoring Program.

Among the important conclusions of the review, we first note that the AZMP meets the international standards needed to contribute to a sustained, systematic, and long-term observation system that provides end products and services about the state of marine ecosystem. A second important conclusion is that the availability of ships to carry out the sampling required for maintaining the program's effectiveness remains one of the most critical issues facing the scientists working to provide a comprehensive overview of oceanographic conditions in the Atlantic zone. On the other hand, the program has provided major input to the eastern Scotian Shelf ecosystem review and played a key role in identifying the invasion of the Gulf of St. Lawrence by the Pacific phytoplankton species *Neodenticula seminae*. The AZMP also provides basic annual information on the oceanographic conditions (physical, chemical, and lower trophic level biology) in the Atlantic

Au cours du développement du programme de monitorage de la zone Atlantique (PMZA), Therriault et al. (1998) ont prévu une revue périodique des progrès du programme à tous les cinq ans comme élément clé afin d'assurer la meilleure utilisation possible des ressources scientifiques et opérationnelles dédiées à l'évaluation en continue des conditions océanographiques de la côte est du Canada. À cette fin, les membres du PMZA, ainsi que les scientifiques du comité d'océanographie des pêches et d'autres groupes de clients, ont identifié une série de critères objectifs pour (1) évaluer le progrès du PMZA par rapport à la poursuite des objectifs énoncés dans la proposition originale (Therriault et. al. 1998), (2) identifier les forces et les limitations de la collecte de données et de leur interprétation, et (3) déterminer les améliorations à apporter pour rendre le programme plus efficace. Le présent article fournit un sommaire des principales conclusions auxquelles en est arrivée la première revue de cinq ans du Programme de Monitorage de la Zone Atlantique.

Parmi les grandes conclusions de la revue on note d'abord que le PMZA rencontre les standards internationaux nécessaires pour contribuer à un système d'observation soutenu, systématique et à long terme qui fournit des produits et services sur l'état de l'écosystème marin. Une seconde conclusion importante est que la disponibilité des navires pour effectuer l'échantillonnage requis pour maintenir l'efficacité du programme demeure l'un des enjeux les plus critiques auquel ont à faire face les scientifiques travaillant à fournir une revue complète des conditions océanographiques dans la zone Atlantique. Par ailleurs, le programme a fourni des données essentielles pour la revue de l'écosystème de la partie est du plateau Néo-Écossais, et a joué un rôle clé dans l'identification de l'invasion du golfe du Saint-Laurent par l'espèce de phytoplancton du Pacifique, *Neodenticula seminae*. Le PMZA fourni aussi annuellement de l'information de base sur les conditions zone to the Fisheries Oceanography Committee, the Canadian Science Advisory Secretariat (research documents and status reports), and NAFO (research document series). It also produces the annual AZMP Bulletin containing an annual environmental review as well as other important AZMP-related information. Finally, AZMP has been identified as a foundation program for Canadian contributions to GOOS (Global Ocean Observation System) as well as to other national and international ecosystem observation and monitoring networks such as GEOSS (Global Earth Observation System of Systems).

As a result of the implementation of the program, there has been a major increase in biological and chemical sampling, leading to a greatly enhanced description and understanding of the ecosystem and a strong, cooperative, coordinated and consistent effort among the regions to provide a thorough assessment of environmental conditions across the Atlantic Zone. The AZMP has met the original objectives of developing and implementing an observational program, but the degree to which seasonal, interannual and decadal variations can be characterized varies among the variables being monitored (Table 1). The ability of AZMP to resolve seasonal and interannual variability is greatest for physical variables and weakest for biological variables, due in part to the limited time series available for the latter. There are highly resolved (in space and time) climatological atlases for the physical variables throughout the Atlantic zone, and very basic climatologies of nutrients for the Gulf of St. Lawrence and the Scotian Shelf–Gulf of Maine. However, considerable gaps remain in the information concerning phytoplankton and zooplankton in many parts of the zone. In general, winter sampling remains very limited because of logistic difficulties (Fig. 1), and even a moderate increase in observations would be of great benefit to establishing the state of the marine ecosystems.

There are also regions that have limited coverage, including the northern Gulf of St. Lawrence, the Labrador and NE Newfoundland shelves, and the south coast of Newfoundland. Nowhere is sampling excessive. Scientists working within the program are making efforts to enhance the coverage in order to overcome some of the data gaps through greater use of ships-of-opportunity and through the redirection of resources and increased collaboration with

Table 1 Variables resolved on three times scales.

Variables résolues selon trois échelles de temps.

Variables / Variables	Scale / Échelle		
	Seasonal / Saisonnière	Interannual[1] / Interannuelle[1]	Decadal / Décadale
Biological (chlorophyll, plankton, optical properties)	Surface chlorophyll everywhere, chlorophyll and plankton at fixed sites (except Shediac Valley), along CPR lines and their representative areas along AZMP sections	Southern Gulf of St. Lawrence (SGSL), Scotian Shelf and Gulf of Maine (SSGoM), Georges Bank	Everywhere[2]
Biologiques *(chlorophylle, plankton et propriétés optiques)*	*Chlorophylle de surface partout, chlorophylle et plancton aux stations fixes (excepté Shédiac Valley), le long des lignes CPR et leurs régions représentatives le long des transects PMZA*	*Sud du golfe du Saint-Laurent (SGSL), plateau Néo-Écossais et golfe du Maine (PNEGM), banc Georges*	*Partout[2]*
Chemical (nutrients, oxygen)	Fixed stations and their representative areas, Eastern Scotian Shelf (ESS) along AZMP sections	SGSL, SSGoM, Georges Bank	Everywhere[2]
Chimique *(sels nutritifs et oxygène)*	*Stations fixes et leur régions représentatives, région est du plateau Néo-Écossais (EPNE) le long des transects du PMZA*	*SGSL, PNEGM, banc Georges*	*Partout[2]*
Physical (temperature, salinity)	Sea surface temperature everywhere, fixed stations and their representative areas, ESS, other limited areas, year-round Long Term Temperature Monitoring Program stations	Everywhere[2]	Everywhere[2]
Physique *(température et salinité)*	*Température de surface partout, aux stations fixes et leur régions représentative, EPNE, autres régions limitées, à l'année longue, stations du programme de monitorage de la température à long terme*	*Partout[2]*	*Partout[2]*

1: all areas described under the seasonal category carry over to longer time scales; 2: in some cases interannual or decadal variability is resolved for a particular season but only that season.
1 : toutes les régions sous échantillonnage saisonnier jusqu'aux plus longues échelles; 2 : dans certains cas la variabilité interannuelle ou décadale est résolue pour une saison particulière mais seulement pour cette saison.

océanographiques (physiques, chimiques et biologie des niveaux trophiques inférieurs) pour le comité d'océanographie des pêches, le Secrétariat canadien de consultation scientifique (documents de recherche et rapports d'état), et l'OPANO (documents de recherche). Il produit également le Bulletin annuel du PMZA contenant une revue environnementale ainsi que d'autres informations importantes reliées au PMZA. Finalement, le PMZA a été identifié comme le programme de base pour fournir les contributions canadiennes à GOOS (« Global Ocean Observation System ») ainsi qu'à d'autres réseaux nationaux et internationaux d'information et de monitorage sur les écosystèmes comme GEOSS (« Global Earth Observation System of Systems »).

Comme résultat de la mise en opération du programme, il y a eu une augmentation majeure de l'échantillonnage biologique et chimique menant à une description et une compréhension grandement améliorée de l'écosystème. Des efforts importants, coopératifs et cohérents entre les régions ont été consentis afin de fournir une évaluation approfondie des conditions environnementales pour toute la zone Atlantique. Le PMZA a rencontré ses objectifs originaux de développer et d'implanter un programme d'observation, mais le degré avec lequel les variations saisonnières, interannuelles et décadales peuvent être caractérisées dépend de la variable qui est monitorée (Tableau 1). La capacité du PMZA à résoudre la variabilité saisonnière et interannuelle est plus forte pour les variables physiques, et plus faible pour les variables biologiques, en raison des limites imposées par la disponibilité de séries temporelles pour ces dernières. Il existe des atlas climatologiques à haute résolution (dans le temps et l'espace) pour les variables physiques de toute la zone Atlantique, et des climatologies élémentaires pour les sels nutritifs pour le golfe du Saint-Laurent et la région du plateau Néo-Écossais et du golfe du Maine : il demeure cependant des trous considérables d'information sur le phytoplancton et le zooplancton dans plusieurs parties de cette zone. En général, l'échantillonnage d'hiver demeure très limité en raison de difficultés logistiques (Fig. 1) et même une augmentation modérée d'observations durant cette période serait grandement bénéfique pour établir l'état des écosystèmes marins.

Il y a aussi des régions où la couverture est limitée incluant la partie nord du golfe du Saint-Laurent, les plateaux du Labrador et du nord-est de Terre-Neuve, ainsi que la côte sud de Terre-Neuve. Nulle part, l'échantillonnage n'est excessif. Les scienother monitoring activities. To date, much of the emphasis by the scientists in the program has been dedicated toward the collection and description of data as part of AZMP annual reporting of the state of the marine ecosystem. However, there was consensus during the review that greater efforts need to be placed on modelling and analyses directed at a more comprehensive analysis of marine ecosystems. The limited progress on providing an overall synthesis of the complex data set that is collected by the AZMP is simply a reflection of the amount of work required for the implementation of an undertaking with the breadth of AZMP. As a result of the review, the researchers connected with the program have begun to draft a synthesis of the oceanographic observations at the six fixed stations of the Atlantic Zone Monitoring Program for 1999-2004 as a starting point for further analysis and modelling. This synthesis paper will be submitted to a peer-reviewed journal in 2005.

There are resources that could make the program more effective, including greater use of new technologies (e.g., satellite and in situ sensors), databases and modelling. These would enhance aspects of the monitoring program and increase long-term efficiency. Isolated sites that are difficult to sample frequently and regularly would be primary areas where the deployment of instrumented moorings could significantly enhance the AZMP's ability to provide a more complete overview of oceanographic conditions and fill in some of the observational gaps mentioned above.

Research at both the Rimouski and Halifax 2 stations has demonstrated the effectiveness of instrumented moorings, although further developments are required to sample all variables included in the monitoring program. However, current resources within AZMP for development and operationalization are modest. The implementation of instrumented sites would require capital investment and infrastructure support to achieve the long-term objectives of the program.

To summarize briefly, AZMP provides a multidisciplinary assessment of the status of the marine environment and draws on other monitoring activities to provide a more thor-

http://www.osl.gc.ca/teledetection/en/index.html

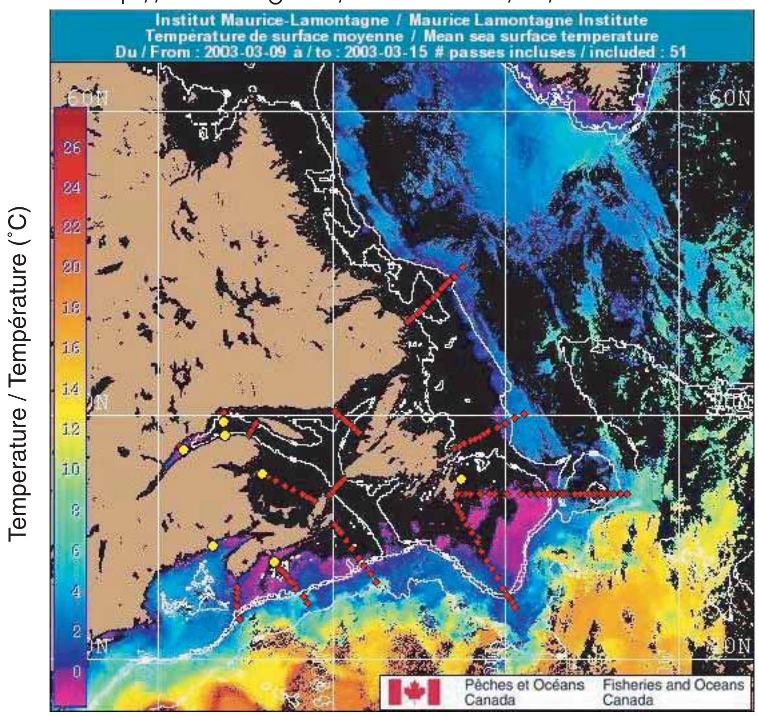

Fig. 1 Remote sensing map of surface temperature showing the extensive sea-ice cover (in black) in mid March 2003 and the locations of the fixed stations (yellow dots) and those (red squares) located along the sampling sections. This image illustrates the difficulty faced by the AZMP to carry out sampling during the winter period and also emphasizes the spatio-temporal limitations of a sampling program having only a very limited number of sampling locations in a hydrologically complex region extending over hundreds of thousands of square kilometres. The stations on sections are only visited 1-3 times per year and the fixed stations 5-10 times per year.

Carte de télédétection de la température de surface montrant la couverture extensive de la glace de mer (en noir) à la mi mars 2003, ainsi que les positions des stations fixes (points jaunes) et de celles (carrés rouges) localisées le long des transects d'échantillonnage. Cette image illustre bien la difficulté du PMZA à effectuer des échantillonnages en période hivernale, et fait aussi ressortir les limitations spatio-temporelles d'un programme d'échantillonnage ne possédant qu'un nombre très limité de stations dans une région hydrologiquement complexe, s'étendant sur des centaine de milliers de kilomètres carrés. Les stations des transects sont seulement visitées de 1-3 fois par année et les stations fixes de 5 à 10 fois par année.

tifiques du programme font également des efforts pour améliorer la couverture dans le but de d'atténuer le problème de manque de données via une plus grande utilisation de temps de navire d'opportunité, la redirection de ressources et une collaboration accrue avec les autres activités de monitorage. À date, la grande partie des efforts des scientifiques du programme a été consacrée à la collection et la description des données via le processus de production de rapports annuels du PMZA sur l'état de l'environnement. Cependant, il y eu consensus durant la revue pour affirmer qu'on a besoin de plus d'efforts d'analyse et de modélisation dirigés vers une compréhension plus globale des écosystèmes marins. Le progrès limité afin de fournir une synthèse globale des bases de données complexes qui sont récoltées par le PMZA reflète simplement la grande quantité de travail qui est requise pour l'implantation d'une initiative de l'ampleur du PMZA. Comme résultat de la revue, les chercheurs du programme ont commencé à planifier une synthèse des observations océanographiques aux six stations fixes du PMZA pour 1999-2004, comme point de départ pour des analyses plus poussées et de la modélisation. Il est prévu de soumettre cette synthèse à un journal arbitré par les pairs en 2005.

Il y a des ressources qui pourraient rendre le programme plus efficace, incluant une plus grande utilisation de nouvelle technologies (ex., senseurs satellites et in situ), de nouvelles bases de données et de la modélisation. Celles-ci amélioreraient certains aspects du programme de monitorage et en augmenteraient l'efficacité à long terme. Les sites isolés qui sont difficiles à échantillonner fréquemment et régulièrement sont les principales cibles où le déploiement de mouillages instrumentés pourrait significativement améliorer la capacité du PMZA à fournir une vue plus complète des conditions océanographiques et pourrait pallier à notre manque d'observations mentionné plus haut.

La recherche à la station fixe de Rimouski et à la Station 2 au large de Halifax démontre l'efficacité des mouillages d'instruments, quoique plus de développement pour fournir le monitorage de toutes les variables du PMZA est encore requis. Cependant, les ressources actuelles du PMZA pour le ough perspective. Overall, the implementation of the AZMP has provided Canadians with an enhanced view of the state of the marine ecosystem as well as with new insights into the interactions among the elements therein. The strength of the program lies in the effective, consistent and continued observation of key variables through the collaborative effort of a large number of biologists, chemists, physicists, data managers, support personnel and ships' crews from many sectors of the Department of Fisheries and Oceans. While enhancements to existing databases (e.g., through incorporation of historical data) are continuing in order to improve understanding and broaden the scope of the program, greater progress should be achieved through more scientific effort directed toward the synthesis and interpretation of the complex multidisciplinary information that forms the basis of the AZMP.

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développement et l'opérationnalisation sont modestes et l'implantation de sites instrumentés requiert plus d'investissements en capital et un support d'infrastructure accrue pour arriver à atteindre les objectifs à long terme du programme.

Pour résumer brièvement, le PMZA fournit une évaluation multidisciplinaire de l'état de l'environnement marin et puise dans les autres activités de monitorage pour fournir une perspective plus approfondie. Globalement, l'implantation du PMZA a fourni aux Canadiens une vue améliorée de l'état de l'écosystème marin aussi bien qu'il a fourni une nouvelle vision sur les interactions entre les divers éléments inclus dans le programme. La force du programme repose dans l'observation effective, consistante et continue de variables clés via l'effort de collaboration concerté d'un grand nombre de biologistes, chimistes, physiciens, gestionnaires de données, personnel de soutien et membres des équipages des navires appartenant à plusieurs secteurs du Ministère des Pêches et des Océans. Même si des améliorations aux bases de données actuelles (ex., via l'incorporation de données historiques) sont constamment apportées dans le but d'améliorer notre compréhension et d'élargir l'étendue du programme, il est évident que des progrès plus importants seraient atteints si des efforts plus spécifiques étaient dirigés vers la synthèse et l'interprétation de l'information multidisciplinaire complexe qui forme la base du PMZA.

The Atlantic Zone Monitoring Program after 5 Years: A Focal Point for Monitoring the Marine Environment of the East Coast

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Sommaire

Au cours de ses cinq premières années d'existence, le Programme de Monitorage de la Zone Atlantique (PMZA) est devenu le point de mire pour le monitorage océanographique et écosystémique sur la côte est du Canada. À titre de fournisseur d'information, client et défenseur/porte-parole, le programme a été un catalyseur pour une large gamme d'activités incluant la collecte et l'analyse de données, le développement technologique et la dissémination de l'information.

En prenant avantage des efforts de monitorage pré-existants, le PMZA a créé le noyau d'un programme de monitorage environnemental de base qui s'est fondé sur plusieurs sections et stations océanographiques qui ont une histoire d'observation qui couvre plusieurs décennies. Plusieurs autres programmes tels que le programme CPR (« Continuous Plankton Recorder »), le programme de monitorage de température à long terme (LTTM), les missions d'échantillonnage environnemental et d'évaluation de stock de poissons à grande échelle spatiale, la télédétection, le réseau des niveaux d'eau, et les missions de prévision des glaces ont également été intégrés au PMZA via des partenariats visant à mettre sur pied un programme de monitorage aussi complet que possible avec les ressources disponibles. Par ailleurs, le PMZA a supporté et encouragé les innovations technologiques alternatives, incluant la télédétection et le développement de nouveaux instruments, afin de complémenter et/ou de remplacer les méthodes d'échantillonnage traditionnelles. L'intégration des protocoles d'échantillonnage de même que la gestion et la dissémination des données sont également des composantes clefs du PMZA qui favorisent le support et développement ordonné des bases de données ainsi que des activités régionales ciblées d'analyse et de diffusion des données de monitorage.

Finalement, les principes de base sur lesquels reposent le développement et l'implantation du PMZA s'alignent bien avec les nouvelles initiatives internationales de monitorage comme GOOS (« Global Ocean Observing System ») et GEOSS (« Global Earth Observation System of Systems ») et, de ce fait, le PMZA est très bien positionné pour jouer un rôle de premier plan pour permettre au Canada de rencontrer ses engagements internationaux.

In the five years since its inception, the Atlantic Zone Monitoring Program (AZMP) has become the focus for oceanographic and ecosystem monitoring on the Canadian east coast. As an information provider, client, and advocate, the program has been a catalyst for a range of monitoring activities that include data collection and analysis, technological developments, and information dissemination.

Program Overview

The AZMP was established to provide a spatially broad seasonal description of the biological, chemical, and physical ecosystem (Petrie and Therriault 2001). The program was designed to make extensive use of existing monitoring programs and extend these where necessary.

The sampling strategy is based on seasonal or opportunistic sampling of sections with higher frequency temporal sampling at more accessible fixed stations (Fig. 1). Data from groundfish surveys, remote sensing, and other existing monitoring programs further enhance the program.

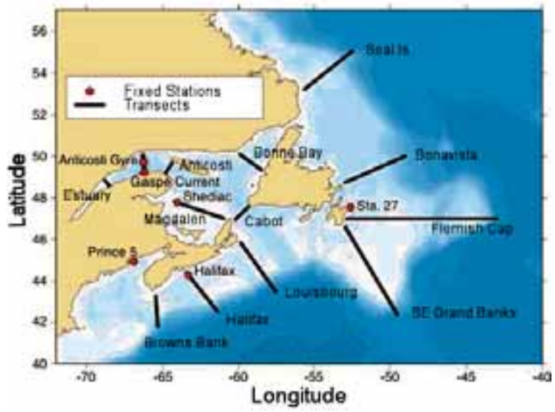

Fig. 1 Fixed Stations and Sections of the Atlantic Zone Monitoring Program.

Stations fixes et transects du Programme de Monitorage de la Zone Atlantique.

"Adopted" Programs

From the beginning, the intent of AZMP was to take advantage of the many existing monitoring efforts and integrate these into a coordinated zonal program. AZMP has been very successful in accomplishing this. A few examples of this integration under the AZMP umbrella include:

- The Prince 5 station near St. Andrews NB (sampled regularly since 1924) and Station 27 off St. John's NL (Colbourne and Fitzpatrick 2003) (since 1946) have oceanographic time series spanning many decades and were obvious candidates for the fixed station component of the observation program. As part of AZMP, biological and chemical sampling are now conducted routinely at these stations.

- The Flemish Cap, Bonavista, and Seal Island lines (Colbourne and Fitzpatrick 2004) were initiated by the Fisheries Research Board of Canada in the late 1940s and early 1950s and have been monitored continuously on an annual basis for physical properties under the auspices of the International Commission for the Northwest Atlantic Fisheries (ICNAF). The Halifax, Cabot, Louisbourg and Browns lines, also started by ICNAF in the 1950s and monitored until the mid 1970s, have been reinstated as standard sections and supplemented with the AZMP suite of biological, chemical, and physical variables. Similarly, the Sept-Îles and Honguedo Strait sections coincide with the location of temperature and salinity measurements that began in 1947 and have been sampled in most years since then.

- The Continuous Plankton Recorder (CPR) program (Sameoto 2001, Brander and Drinkwater 2003), operated for DFO by the Sir Alister Hardy Foundation for Ocean Science, is based on sampling from commercial trans-Atlantic shipping vessels and is incorporated into the AZMP program. Two transect lines (Fig. 2), the Z-line, running between Iceland and Newfoundland, and the E-line, between Newfoundland and Boston, provide the longest data series of phytoplankton and zooplankton species composition in the northwestern Atlantic. Collection on the Z-line began in 1959, broke from 1986-1991, and has continued since then. The E-line ran from 1961-1976 and was reinstated in 1991.

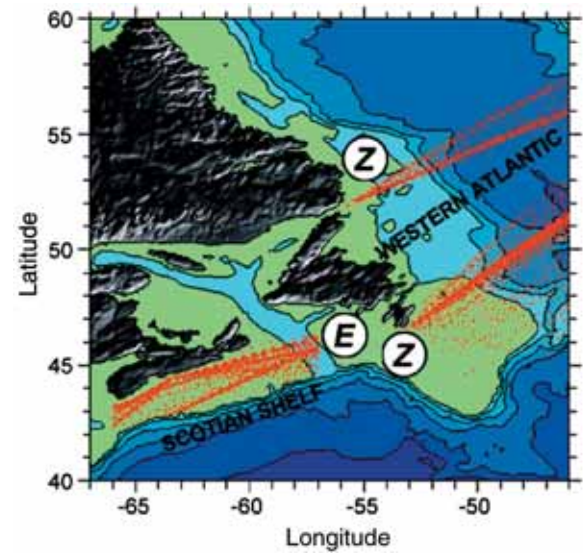

Fig. 2 Lines E and Z of the Continuous Plankton Recorder surveys.

Lignes E et Z des missions CPR (« Continuous Plankton recorder »).

- The Long Term Temperature Monitoring (LTTM) programs in the Maritimes, Newfoundland and Québec regions have been making near-shore temperature measurements in Newfoundland since the late 1960s and from the Scotian Shelf, Bay of Fundy, and Gulf of St. Lawrence since the late 1970s.

- Winter oceanographic conditions in the Gulf of St. Lawrence have been monitored by the Institut Maurice-Lamontagne (IML) since 1996 using a helicopter-based survey. The winter water masses are identified as well as the depth of the surface near-freezing mixed layer. Surface nutrients have also been collected in recent years.

- Standardized environmental indices and environmental overviews prepared for the Fisheries Oceanography Committee (FOC) are integral parts of the analysis and reporting of the AZMP. These include air temperature, winds at various locations, freshwater discharge through major coastal drainage basins, and regional ice distributions. Additional specialized oceanographic indices such as the North Atlantic Oscillation (NAO index time series), the cross-sectional area of the cold intermediate layer (CIL) over the Grand Banks (Bonavista, Flemish Cap, and Seal Island lines), and layer-averaged temperatures in the Gulf of St. Lawrence are also maintained.

In addition, the AZMP, through FOC, also reports annually on the results of ongoing monitoring programs to investigate large, climate-scale processes of the NW Atlantic as well as more localized human influences on coastal ecosystems. Some of the programs reported by AZMP are:

- Over the past 40 years, the Labrador Sea program has documented decadal variability in the intensity of winter mixing or convection (Fig. 3) and its consequences on the Labrador Current. During the last decade, observations have expanded to include marine chemistry (nutrients, carbon dioxide) and biology (phytoplankton, bacteria, zooplankton). These observations provide an "upstream" context for interpreting ecosystem and environmental changes in the AZMP region.

Fig. 3 Labrador Sea Line AR7W and Station Bravo.

Ligne AR7W dans la mer du Labrador et Station Bravo.

- Since 1991, the Rimouski Station monitoring program has measured the interannual and decadal physical and biological variability in the Lower St. Lawrence Estuary. Observations were expanded in 1999 to include weekly biochemistry observations from May to October, including nutrients, oxygen, pH, primary production, plankton composition and abundance, and bacterial and viral abundance. The Rimouski Station is now fully integrated with the AZMP.

- Since 1994, a zooplankton biomass survey has been carried out in the Lower Estuary and the northwest Gulf of St. Lawrence in September of every year. This survey provides AZMP with data on the biomass and abundance of the macrozooplankton including euphausiids (krill), which represent a keystone species of marine ecosystems and a major constituent of the diet of a variety of species in the GSL, including fish, invertebrates, and marine mammals.

- The 30-year Bedford Basin monitoring program, which includes weekly to monthly physical, biological, and chemical observations, has documented the influence of human activity on a coastal ecosystem and provides an important contrast with the more pristine waters of the open shelf monitored by the AZMP.

Partnerships

The annual groundfish and invertebrate fisheries surveys (Frank 2004, Harrison et al. 2004) are viewed as a vital component of the zonal monitoring program. Many of these standardized surveys go back to 1970 and have continued uninterrupted to the present. In addition to providing a time-series of stock abundance and distribution, these surveys have routinely made temperature and salinity observations, contributing significantly to DFO's physical observation program. With the development of AZMP, these surveys have expanded to include observations of nutrients, oxygen, chlorophyll, and zooplankton. As an example, the 2002 field season (Fig. 4) resulted in over 2400 stations distributed over the entire zone and all four seasons.

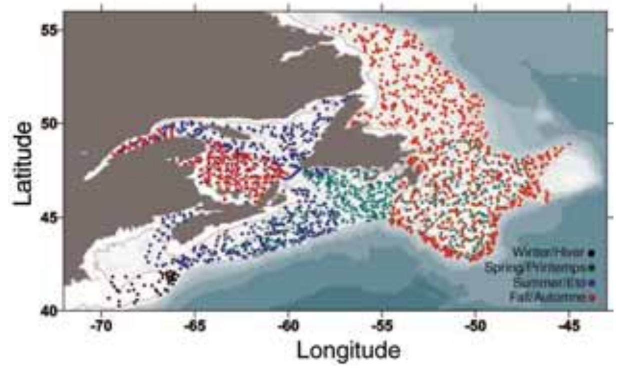

Fig. 4 AZMP Stations from groundfish and pelagic surveys during 2002.

Stations PMZA des missions d'évaluation des poissons pélagiques et de fond au cours de 2002.

Since the early 1960s, DFO has conducted an annual Ice Forecast cruise in the Gulf of St. Lawrence on behalf of the Canadian Ice Service of Environment Canada. Initially run out of the Bedford Institute of Oceanography (BIO), the November cruise has been conducted by IML since the mid 1990s. Temperature data from the cruise are used to predict freeze-up in the Gulf. Nutrient and oxygen observations are also made on an opportunistic basis to supplement monitoring in the Gulf. Sampling of the Gulf of St. Lawrence AZMP transects has been incorporated into the Ice Forecast cruise since the beginning of AZMP, providing early winter data.

The Canadian Hydrographic Service (http://www.waterlevels-niveauxdeau.gc.ca) maintains a sea-level network of tide gauges throughout Atlantic Canada. AZMP, through its web site (http://www.meds-sdmm.dfo-mpo.gc.ca/zmp/main_zmp_e.html), routinely reports on nine sea-level locations within the zone. In addition, AZMP uses the Halifax Station in its annual report to the FOC. The Halifax Station and another to be established on the Labrador coast are part of Canada's proposed contribution to the Global Earth Observation System of Systems (http://www.epa.gov/geoss/).

Technology Development and Innovation

Monitoring the ocean environment makes huge demands on AZMP funding, vessel time, and personnel. As our understanding of the environment increases, there is a demand for higher quality observations at greater spatial and temporal resolution. As part of its mandate, AZMP has supported, encouraged, and adopted innovative alternatives to conventional sampling from vessels.

Remote sensing from satellites provides temporal and spatial detail that is unattainable with conventional sampling and has become an integral part of the AZMP program. The types of observations available to AZMP are sea-surface temperature (NOAA), ocean colour (SeaWiFS, to be replaced by MODIS), and sea-surface topography (TOPEX / Poseidon and Jason-1). Ocean colour can be converted to chlorophyll, a fundamental biological variable. By incorporating phytoplankton biophysical models with sea-surface temperature and chlorophyll concentrations, scientists at the Bedford Institute routinely produce maps of primary production (http://www.mar.dfo-mpo.gc.ca/science/ocean/ias/seawifs/seawifs_1.html). Researchers at IML have developed a system with automatic atmosphere and cloud corrections to produce daily maps of sea-surface temperature (SST) for the entire Atlantic zone. The special problem associated with ocean colour observations in inland seas, where the chlorophyll signal is significantly contaminated by silt and organic matter (yellow substances), is another topic under investigation at IML. Ocean surface topography from satellite altimetry measurements can be used to compute surface currents and volume transports (Fig. 5). Scientists (Han 2004) from the Northwest Atlantic Fisheries Centre (NAFC) are using these data with the objective of producing an environmental index for the Labrador Current.

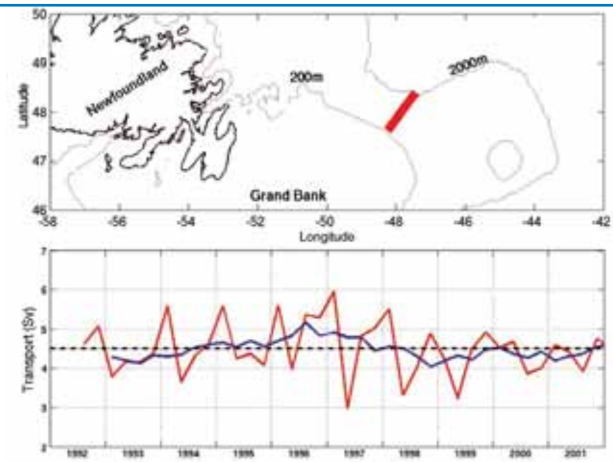

Fig. 5 Variability in the volume transport across a section of the Labrador Current (top figure) estimated from satellite altimetry. Satellite altimetry provides seasonal-mean transport anomalies (red line), complemented with the mean transport from a regional model (dashed line). The blue line shows interannual variability after the annual and semi-annual cycles are removed.

Variabilité du volume de transport à travers une section du courant du Labrador (figure du haut) estimé à partir de l'altimétrie satellitaire. L'altimétrie satellitaire fournit les anomalies saisonnières moyennes du volume de transport (trait rouge), qui sont complémentées par le transport moyen obtenu à partir d'un model régional (trait discontinu). Le trait bleu montre la variabilité interannuelle après que les cycles annuels et semi-annuels aient été enlevés.

Although remote sensing is indispensable for high-resolution and spatially broad observations of the sea surface, high quality in situ observations are required to validate the satellite data and to provide subsurface measurements. To address this need, the AZMP supports a number of innovative sampling technologies. Some of the highlights include:

- Scientists and engineers at the Bedford Institute are working on a number of instruments that will result in significant reductions in the time and effort required to make in situ oceanographic observations (Herman and Hamilton 2002). The Moving Vessel Profiler (MVP) is a towed vehicle and winch system that permits a ship to make profile measurements while the ship travels at speeds up to 14 knots. The Optical Plankton Counter (OPC) is an ongoing development of a towed optical sensor to count and size particles in the size range of zooplankton at high spatial and temporal resolution over large areas. The SeaHorse is an innovative moored ocean profiler that uses wave power to ratchet the package down through the water column and buoyancy to rise to the surface again; it is designed to carry a payload of a variety of oceanographic instruments. The advantages are that the entire water column does not need to be instrumented and the power requirement of the SeaHorse profiler is very low, potentially permitting very long deployments at sea.

Fig. 6 Ocean buoy developed at the Institut Maurice-Lamontagne.

Bouée océanique développée à l'Institut Maurice-Lamontagne.

- Scientists in Newfoundland Region routinely outfit fishing trawls used on the groundfish surveys with conductivity, temperature, and depth recorders. At the Institut Maurice-Lamontagne, commercial and Canadian Coast Guard vessels have been instrumented to measure near-surface temperature and salinity in the Estuary and Gulf of St. Lawrence, providing weekly transits between Montréal and St John's (Galbraith et al. 2002).

- Researchers at IML are also developing and operating a real-time oceanographic buoy network (Larouche and Pettigrew 2003) (Fig. 6) to make surface and atmospheric measurements. These buoys can be adapted to incorporate subsurface instruments. Two buoys are in operation, and a network of five buoys is planned for 2005 with an eventual expansion to eight buoys covering the Gulf of St. Lawrence. The data are collected in real time and are accessible on the Internet via the OSL portal (http://www.osl.gc.ca/).

Information Management and Dissemination

One of the key measures of success of a program like AZMP is how well it communicates its results to clients. From its inception, the AZMP recognized the importance of data management and data dissemination as an integral part of the program. Though now standard practice with new DFO initiatives, it was not the norm when the AZMP was initially proposed. The original mandate required the program "to provide historical and on-line data in support of marine activities" (Petrie and Therriault 2001). A major objective of the program has been the integration of data support activities among the four east coast regions of DFO and the Marine Environmental Data Service (MEDS), the national data center for DFO. The primary focus of AZMP on the Internet is provided by MEDS through its AZMP web site (http://www.meds-sdmm.dfo-mpo.gc.ca/zmp/main_zmp_e.html).

A significant achievement in AZMP data management has been the development of BioChem (Gregory and Narayanan 2003), a web-accessible database of marine biological and chemical data. BioChem would not likely have happened without the enthusiastic support and contributions from AZMP. Initially developed within Maritimes Region, the database is now administered as a national application through MEDS. (http://www.meds-sdmm.dfo-mpo.gc.ca/biochem/biochem_e.htm).

The Institut Maurice-Lamontagne maintains the OSL Internet portal (St. Lawrence Observatory; http://www.osl.gc.ca/), which provides access to a variety of data and data products for the Estuary and Gulf of St. Lawrence. The OSL hosts IML's Oceanographic Data Management System (ODMS), which provides access to archived oceanographic data for the St. Lawrence region, the toxic algae monitoring data, the real-time buoy network data, and the thermosalinograph data. While the OSL is not formally a part of AZMP, it relies heavily on AZMP for a number of the data products it provides.

The Bedford Institute provides a number of web-accessible databases (http://www.mar.dfo-mpo.gc.ca/science/ocean/database/data_query.html) for which AZMP is a major client and supporter. One such database, called Climate, is an archive of temperature and salinity profiles for the Northwest Atlantic dating back to the *Challenger* expedition in the 1870s. Climate incorporates data obtained through national and international exchange programs by MEDS. Coastal Time Series (CTS) is a database of coastal thermographs acquired through the Long-Term Temperature Monitoring Program in the Gulf, Maritimes, Newfoundland, and Québec regions. The Ocean Data Inventory (ODI) is a collection of the statistics of time series measurements of currents, temperature, and water level from the east coast of Canada. The SST (sea-surface temperature) and OCDB (Ocean Colour Database) provide remotely sensed data as discrete values so that they may be treated in the same manner as conventional observations collected from moored or ship-borne sensors.

Future

Monitoring the ocean on a global scale is the objective of two international initiatives. The Global Ocean Observing System (GOOS) (http://ioc.unesco.org/goos/) was first proposed in the early 1990s and has both global climate and coastal modules. More recently in 2003, 33 nations including Canada met in Washington D.C. for the Earth Observation Summit. One of the results was the launch of the Global Earth Observation System of Systems (GEOSS) (http://www.epa.gov/geoss/). The Canadian planning organization for GEOSS is called the CGEO (Canadian Group on Earth Observations) (http://www.cgeo-gcot.gc.ca/).

AZMP is poised to play an important role in meeting Canadian marine needs as well as fulfilling Canada's international commitments through participation in GOOS and GEOSS. The principles upon which AZMP was developed and implemented align well with those of both GOOS and GEOSS. Chief among these are a commitment to a sustained, systematic, long-term observation system that is cost-effective, employs standardized methodologies and quality assurance, has an open data policy, is subject to periodic review, and is adaptable and responsive to end-user needs.

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Oceanographic Observations and Data Products Derived From Large-Scale Fisheries Resource Assessment and Environmental Surveys in the Atlantic Zone

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Sommaire

Les grands relevés standard d'évaluation de poissons pélagiques, démersaux et d'invertébrés commerciaux, ainsi que de plancton (krill) et des variables environnementales comme la température et la salinité, plusieurs en cours depuis le début des années 1970, sont les principales sources de données qui sont utilisées par le PMZA pour caractériser la variabilité spatiale des propriétés océanographiques (physique, biologique et chimique) dans la zone Atlantique. Approximativement 2,500 stations et sites de pêche sont échantillonnés annuellement. Dans le passé, les propriétés hydrographiques (température, salinité et densité) étaient les plus communément mesurées mais des mesures biologiques (abondance du plancton et chlorophylle) et chimiques (oxygène et sels nutritifs) ont été ajoutées à plusieurs missions depuis que le PMZA a débuté en 1999. En plus de fournir des estimations de la variabilité spatiale des conditions océanographiques des régions surveillées, plusieurs produits de données à valeur ajoutée sont générés de façon routinière pour caractériser l'habitat océanographique. Parmi les produits basés sur la surface couverte, on note la température du fond (i.e., l'index thermal de l'habitat ou « Thermal Habitat Index ») et la saturation des eaux du fond en oxygène. Parmi les produits de données basés sur le volume, on note la CIF (couche intermédiaire froide) pour le golfe du Saint-Laurent, les indices de masse d'eau basés sur les propriétés de température et de salinité, les indices de stratification de la colonne d'eau et les patrons spatiaux de la structure verticale du phytoplancton (la fluorescence). Les nouvelles applications en cours incluent les efforts pour lier le forçage à grande échelle de la météorologie (e.g., indice ONA ou « NAO ») aux habitats et à la distribution des poissons.

Introduction

The collection of oceanographic data aboard fisheries resource assessment surveys, initiated over 30 years ago in the northwest Altantic, was motivated by the belief of some fisheries scientists and oceanographers that changes in the near-bottom thermal habitat could be related to the distribution and abundance of commercially important groundfish species. After the collapse of northern cod and other groundfish species in the early 1990s, there was an urgent need to begin examining these data in the broader context of fish production and ocean climate variability. At about the same time, international (Northwest Atlantic Fisheries Organization, NAFO), zonal (Fisheries Oceanography Committee, FOC) and regional (resource assessment proceedings, RAPs) groups began examining and reporting these data in a more detailed and systematic way. Initially, the focus was on characterizing the climatological conditions of the bottom habitat of cod and other species as well as providing descriptions of year-to-year habitat changes. Beginning in the mid-1990s, analysis of oceanographic data extended beyond these basic descriptions to investigate linkages between temperature and salinity variability in space and time and the distribution and abundance of finfish and invertebrate species.

Table 1 Large-scale marine resource assessment and environmental surveys providing oceanographic data for AZMP.

Missions d'évaluation des ressources marines et de monitorage environnemental à grande échelle fournissant des données pour le PMZA.

Survey	Region covered (NAFO)	Start Year	Occurrence	No. Stns. (2002)	Variables[1]
Groundfish	Georges Bank (5X)	1986	Winter	89	H-B-C
Groundfish	Eastern Scotian Shelf (4VW)	1986	Spring	121	H-B-C
Groundfish	S Nfld Shelf/Grand Banks (3Ps, 3LNO)	1971	Spring	684	H
Helicopter	Gulf of St. Lawrence (4RS)	1996	Spring	67	H-C
Groundfish	Scotian Shelf (4VWX)	1970	Summer	212	H-B-C
Shrimp	Gulf of St. Lawrence (4RS)	1983	Summer	211	H-B-C
Mackerel	S. Gulf of St. Lawrence (4T)	1982	Summer	70	H-B-C
Krill	Estuary (4T)	1994	Summer	45	H-B-C
Groundfish	S. Gulf of St. Lawrence (4T)	1971	Fall	175	H-B-C
Groundfish	Labrador/Grand Banks (2J, 3KLNO)	1977	Fall	765	H
Ice	Gulf of St. Lawrence (4RS)	1960s	Fall	79	H-B-C
TOTAL				2,518	

1: H=Hydrography (XBT and CTD data), B=Biology (bottle and net plankton data), C=Chemistry (oxygen and nutrient data). NOTE: Comprehensive biological and chemical data collections started when AZMP field campaigns began in 1999.

The lack of solid information on and a clear understanding of the contribution of environmental changes to the collapse of the northern cod were important catalysts for the development of the Atlantic Zone Monitoring Program (AZMP). During the early stages of development of the AZMP in the mid-1990s, it was recognized that oceanographic data collected on the various large spatial-scale marine resource assessment (groundfish, pelagics, invertebrates) and other (krill, ice) surveys would constitute a vital component of the new observational program (Therriault et al. 1998). These surveys, some running since 1970 or earlier (Table 1), would not only provide standardized time-series of finfish and large invertebrate abundance and distribution, but would also provide environmental information on temperature and salinity and the opportunity to collect data to better characterize important chemical (oxygen, nutrient concentrations) and biological (phytoplankton/chlorophyll, zooplankton) properties of northwest Atlantic waters.

Since the implementation of AZMP in 1999, these surveys have become the largest source of in situ hydrographic, chemical and biological data, with more than 2500 stations sampled annually (Fig. 1), and are the principal basis for spatial variability indices and data products routinely reported by the AZMP.

Most of the oceanographic data (> 80%) are collected during groundfish surveys (currently referred to as "multi-species" or "ecosystem trawl" surveys) (Table 1). Only 4% of the stations are occupied during the winter (December-February) months; these are confined to Georges Bank (Fig. 1). Approximately one third of the stations are occupied during spring (March-May) and cover a significant part of the Atlantic Zone (i.e., eastern Scotian Shelf, Gulf of St. Lawrence and southern Newfoundland Shelf). Summer surveys (June-August) constitute a little over 20% of the stations and cover the Scotian Shelf and Gulf of St. Lawrence. Fall (September-December) surveys are the most extensive, comprising over 40% of the stations, and cover the Gulf of St. Lawrence and the Newfoundland and Labrador shelves. Most of the stations are sampled by the Newfoundland and Labrador Region (60%), but only hydrographic data are collected on those surveys apart from the fisheries data. Chemical and biological collections on the remaining surveys are generally limited to a subset of the total stations occupied. Although nutrients and fluorescence are measured at most stations, zooplankton net hauls are done at only 10-15% of the hydrographic stations during the four Maritimes groundfish surveys; a greater percentage of stations are sampled for zooplankton on the Québec surveys.

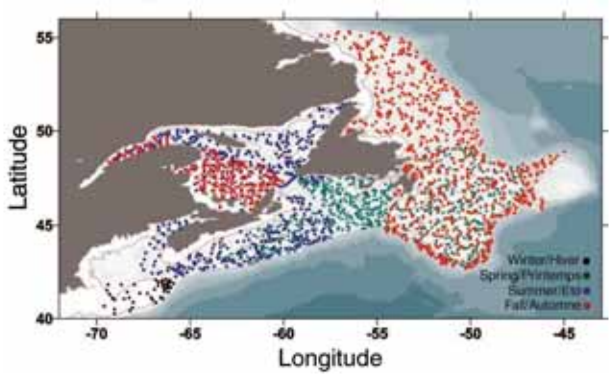

Fig. 1 Map showing the stations occupied during 2002 groundfish, pelagic (mackerel, krill) and environmental (helicopter, ice) surveys from which oceanographic data were collected and processed by the AZMP (colour-coded by season).

Carte montrant les stations occupées durant les missions d'échantillonnage de poissons de fond et pélagiques (maquereau, krill) et les missions environnementales (hélicoptère, glace) pour lesquelles des données océanographiques ont été recueillies et analysées par le PMZA (le code de couleur indique la saison).

Newfoundland and Labrador Surveys

Stratified random bottom trawl surveys have been conducted in NAFO sub-areas 2 and 3 on the Newfoundland and Labrador shelves since 1971. The surveys follow a sampling scheme outlined by Doubleday (1981), whereby areas within each division, with a particular depth range, are divided into strata and the number of fishing stations in an individual stratum are based on an area-weighted proportional allocation. Surveys have been conducted for the following NAFO divisions, time periods and depth ranges: 3P in winter and/or spring from 1972 to 2004, in water depths to 366 m until 1979 and to 548 m since then; 3L in spring from 1971-2004 except 1983 and 1984; 3NO in spring from 1971-2004 except 1983 in 3N and 1972, 1974 and 1983 in 3O, in water depths to 366 m in most years and more recently to 548 m; 2J in fall from 1977-2004; 3K in fall from 1978-2004; 3L in fall from 1981-2004; 3NO in fall from 1990-2004. Traditionally, the surveys were to assess groundfish species, but since the fall of 1995, with the adoption of the Campelen 1800 shrimp trawl (McCallum and Walsh 1996), the surveys now provide abundance and distribution data on northern shrimp and snow crab as well. Oceanographic data collected on the surveys from 1971 to 1988 consisted mainly of temperature profiles at the fishing set locations using mechanical or expendable bathythermographs (MBT/XBT). These were usually deployed at the end of each fishing tow. Occasionally, water sampling bottles fitted with reversing thermometers were used at some stations to collect temperature and salinity data at standard depths. Since 1989, net-mounted conductivity-temperature-depth (Sea-Bird model SBE-19 CTD systems) recorders have replaced XBTs. This system records pressure, temperature and salinity during trawl deployment and recovery and for the duration of the tow. Since the implementation of the net-mounted CTDs, the multi-species surveys provide two spatially comprehensive temperature and salinity data sets annually, one during the spring from 3Pn in the west to 3LNO on the Grand Bank and one during the fall from 2J in the north to 3NO in the south (Fig. 1).

Maritimes and Gulf Surveys

Until 1988, only temperature and salinity data were collected on Maritimes/Gulf groundfish surveys and only at a subset of the fishing set locations. During this period, the number of oceanographic samples collected on each survey grew from a very few during the early years to between a third and a half of all set locations by 1988. Temperature and salinity sampling was by surface buckets and Knudsen reversing bottles at standard ICNAF depths. Additional temperature data were collected using mechanical bathythermographs until 1981 and expendable bathythermographs (XBTs) until 1988. In 1989, Sea-Bird CTDs were introduced and after initial trials were deployed at all stations, provided no additional time was taken. Water sampling bottles with reversing thermometers were also added at 10 m depth or the bottom to obtain water samples for calibrations. Throughout the 1990s, dissolved oxygen (O2), fluorescence and light sensors were added to the CTD. Water sampling bottles were added at 5 m, mid-depth and the bottom for temperature, salinity, nutrients, chlorophyll and O2; Minilog temperature–depth recorders were also added on the foot rope of the trawl. With the initiation of AZMP, vertical plankton tows were added at a subset of stations and full oceanographic measurements (hydrography, chemistry, biology) were done at the AZMP fixed stations. To accommodate the increased ship-time requirement to add oceanographic measurements to the surveys, three days were added to the surveys in the late 1990s. In 2002, the oceanographic sampling took another step with the addition of a winch with electromechanical cable and a modified four-bottle rosette with altimeter for CTD deployment and water sampling. The installation of new equipment has greatly facilitated the profiling of the water column and the collection of physical, chemical and biological data consistent with the standard AZMP protocols.

Québec Surveys

The August shrimp and groundfish surveys in the northern Gulf of St. Lawrence began in 1983. Initially, oceanographic measurements were restricted to XBTs with limited spatial coverage. Complete regional coverage of NAFO area 4RS began in 1984 and CTD measurements replaced XBTs in 1991. Nutrients, oxygen and chlorophyll measurements were performed at all stations in 1995 (Gilbert et al. 1997), and oxygen measurements were performed in 2004. The pelagic mackerel survey in the southern Gulf began in 1982 (Castonguay et al. 1998) and included hydrographic sampling and some limited biological sampling (zooplankton). Krill surveys in the Estuary and adjacent waters began in 1994 and have included hydrography, chemistry (nutrients) and zooplankton net hauls. This survey was integrated into Québec's AZMP annual fall survey in 2004. The November ice forecast survey began in the early 1960s (35 stations scattered throughout the Gulf). These surveys were designed to provide hydrographic data to Environment Canada's Ice Centre to help prepare their freeze-up forecasts for the Gulf. Nutrient and oxygen measurements started in the 1980s and biological measurements were added when the surveys were placed under the AZMP-Québec operations in the late 1990s. The number of stations has essentially doubled (79 in 2002) from the earliest surveys. Most recently (beginning in 1996), spring (March) helicopter CTD surveys were initiated in the Gulf to help establish the importance of the inflow of the Strait of Belle Isle in the formation of the Gulf's cold intermediate layer (CIL). The number of stations sampled has varied over the intervening years (43-69). CTD profiles are confined to the upper 200 m for determining the depth of winter convection. Surface nutrient measurements were added to provide an index of the nutrient pool available for sustaining the upcoming spring phytoplankton bloom.

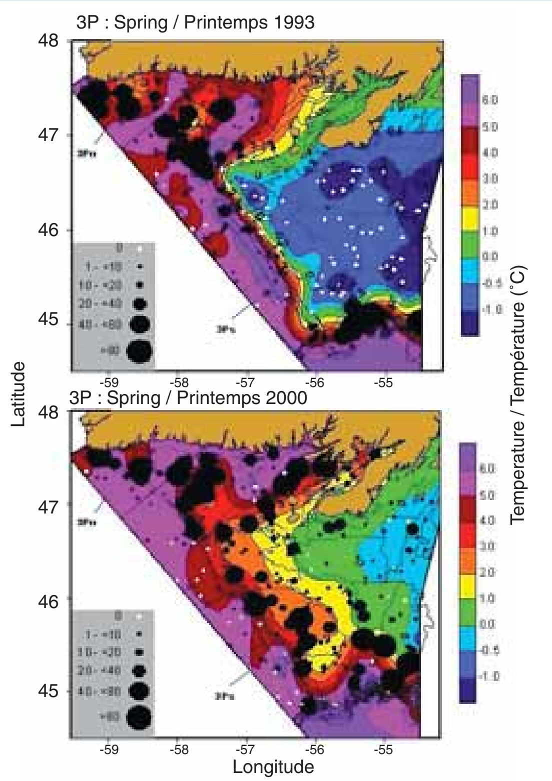

Fig. 2 Bottom temperature contour maps (˚C) for 1993 and 2000 based on data collected during the spring multi-species survey of division 3P. The number of cod in each set is shown as solid expanding circles; white crosses represent zero catch.

Cartes de contour de température (˚C) pour 1993 et 2000 basées sur des données échantillonnées durant la mission multi-espèces de printemps de la division 3P. Le nombre de morue dans chaque trait de chalut est indiqué par des cercles de différente grosseur. Les croix blanches indiquent aucune capture.

Data Products

One of the most useful area-based data products coming out of these surveys has been bottom temperature. In the Newfoundland Region, for example, contoured maps of near-bottom temperature grids for a particular area as well as their anomaly fields (from the 1971-2000 long-term means) are produced (Fig. 2). Horizontal temperature and salinity maps are also produced for other depths, including the surface; however, the estimated anomaly fields for the shallower depths with significant annual cycles are of limited value without extensive analysis since the surveys, which can take up to three months, are not always conducted in the same order each year.

Other related data products are time series of the area of the bottom covered by water in selected temperature ranges, sometimes referred to as the "Thermal Habitat Index" (Fig. 3A). These indices show estimates of the percentage of the total area within each temperature range for the survey. The selected temperature ranges for the Newfoundland Shelf are ≤ 0°C, 0-1°C, 1-2°C, 2-3°C and ≥ 3°C. These ranges provide adequate resolution of the relatively narrow bottom temperature range (–1 to 3°C) in this region. On the Scotian Shelf, the Thermal Habitat Index includes temperature ranges from –1 to 10°C for

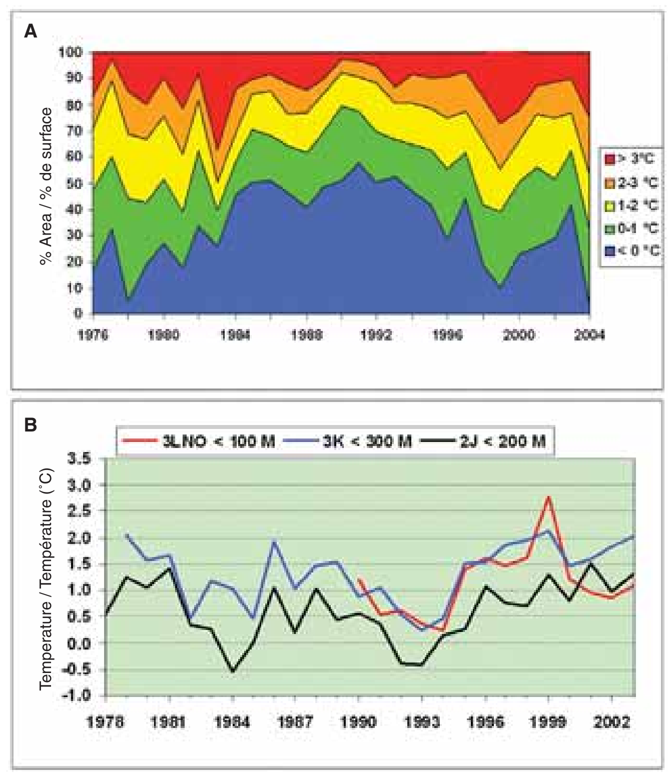

Fig. 3 (A) Time series of the percentage of the bottom area covered by water with temperatures ≤ 0°C, 0-1°C, 1-2°C, 2-3°C and ≥ 3°C during spring in NAFO Div. 3LNO. (B) Time series of the spatially averaged bottom temperatures during the fall on the banks in NAFO Div. 3LNO, 3K and 2J.

(A) Série temporelle du pourcentage de la région du fond couverte par des eaux avec des températures ≤ 0°C, 0-1°C, 1-2°C, 2-3°C et ≥ 3°au printemps dans la division OPANO 3LNO. (B) Série temporelle de la moyenne spatiale des températures du fond durant l'automne sur les bancs des divisions 3LNO, 3K et 2J de l'OPANO.

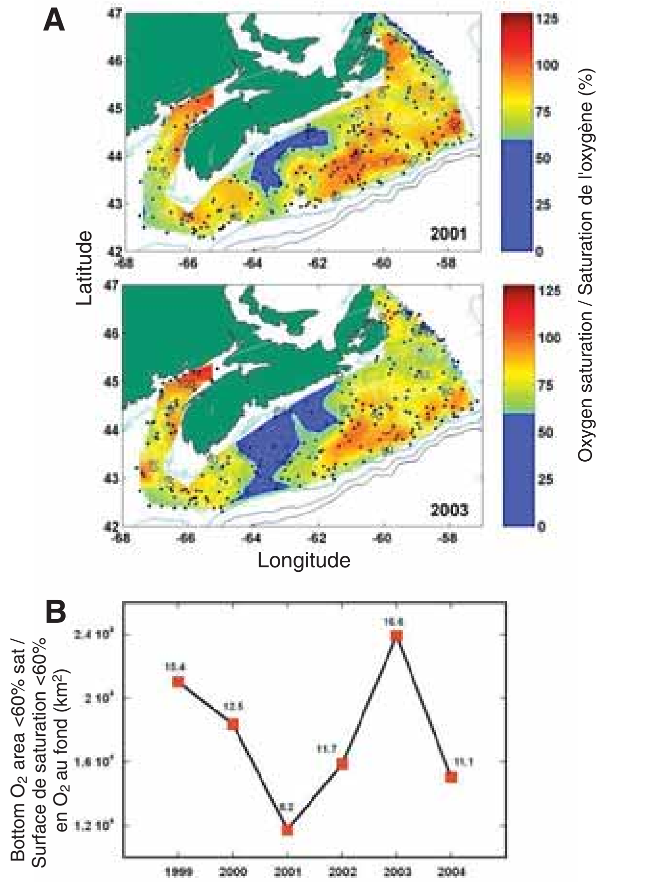

Fig. 4 (A) Contour plots of oxygen saturation (%) in bottom waters of the Scotian Shelf during the annual July groundfish surveys comparing extreme conditions in 2001 and 2003. (B) Year-to-year (1999-2004) variations in area (km^2) occupied by bottom waters with oxygen saturation < 60%. Numbers above symbols are % of total area of the Shelf surveyed.

(A) Carte montrant la répartition de la saturation en oxygène (%) des eaux de fond sur le plateau Néo-Écossais au cours des relevés annuels de poissons de fond de juillet, comparant les conditions extrêmes de 2001 et 2003. (B) Variations interannuelles (1999-2004) de la surface du fond (km^2) occupée par les eaux ayant un pourcentage de saturation < 60%. Les nombres au dessus des points représentent le % de la surface totale échantillonné sur le plateau.

area 4Vn and –1 to 18°C for area 4W. The time series track annual changes and long-term trends in the spatial extent of the thermal habitat affecting various species. Snow crab, for example, may prefer slightly colder temperature ranges than Atlantic cod. A time series of the spatially averaged temperature field for a particular management area or geographic feature, such as a major bank, is also generated from this analysis (Fig. 3B). These show long-term trends and yearly variations in the ocean environment that may influence the growth or distribution of particular species or other aspects of marine productivity.

These data products indicate changes in the near-bottom thermal habitat and effects on the distribution and abundance of the groundfish surveyed. A recent study by Colbourne and Murphy (2003) of cod distribution and temperature in the 3Ps area, for example, showed that in many years the distribution of cod on St. Pierre Bank is potentially influenced by the amount of cold Newfoundland Shelf water present during the surveys (Fig. 2). Colbourne and Kulka (2004) have also linked changes in the thermal habitat and the distribution of thorny skates (*Amblyraja radiata*) in NAFO Div. 3PLNO. A more general application of these data products has been to examine decadal changes in the ocean climate in Newfoundland and Labrador waters (Colbourne 2004) and to assess the biological responses (Colbourne and Anderson 2003).

Ocean chemical properties may also be important in establishing a link between environment and the fisheries. Oxygen saturation levels can strongly influence the physiology and behaviour of fish and may induce negative effects when saturation levels fall below 60% (Plante et al. 1998, Chabot and Dutil 1999). Bottom oxygen concentrations have been routinely measured on the July Scotian Shelf and September southern Gulf surveys since 1999 (Fig. 4A). Bottom water oxygen levels are generally related to depth (deeper waters in Shelf basins or at the Shelf edge have lower oxygen saturation) and

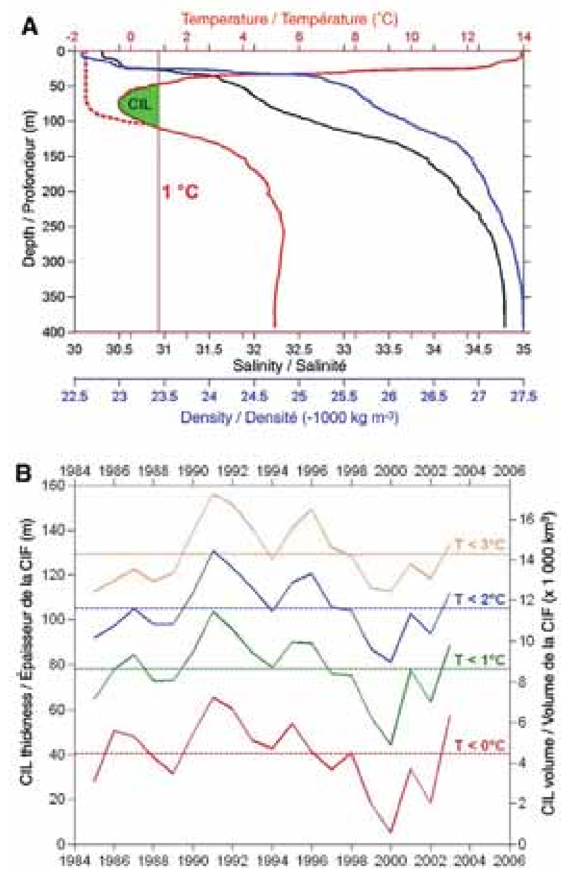

Fig. 5 (A) Typical profile of temperature (red), salinity (black) and density (blue) observed during summer in the Gulf of St. Lawrence. The cold intermediate layer (CIL, in green) is defined as the part of the water column colder than 1°C. The dashed red line shows a schematic winter profile with near-freezing temperatures in the upper 70 m. (B) Time series of the mean CIL thickness (left y-axis) and volume (right y-axis) in the Estuary and Gulf of St. Lawrence during the August-September surveys with different temperature thresholds. The horizontal lines show the 1985-2003 averages.

(A) Profiles typiques de température (rouge), salinité (noir) et densité (bleu) observés au cours de l'été dans le golfe du Saint-Laurent. La couche intermédiaire froide (CIF, en vert) est définie comme la partie de la colonne d'eau où la température est plus froide que 1 °C. La ligne rouge discontinue montre un profile schématique d'hiver avec des températures près du point de congélation dans les premiers 70 m. (B) Séries temporelles de l'épaisseur moyenne et du volume de la CIF dans l'estuaire et le golfe du Saint-Laurent au cours des missions d'août-septembre pour différents niveaux de température. Les lignes horizontales indiquent les moyennes de 1985-2003.

water mass (cold, fresh waters of Labrador origin are generally higher in oxygen than warm, salty slope waters) (Petrie and Yeats 2000). Although the time series is relatively short, large changes in bottom area where percent saturation is less than 60% (termed the "Bottom Oxygen Area Index") have been observed on the Scotian Shelf; the area index varies by as much as a factor of two between surveys (Fig. 4B). Compared to the climatology of bottom water oxygen conditions, the area index in recent years, although variable, is generally smaller than the long-term mean.

The most frequently produced volume-based data product from these large-scale surveys is the volume of the cold intermediate layer (CIL), a relic of winter cooling of surface water defined as waters with temperatures below an arbitrary value (Fig. 5A), generally 1°C in the Gulf of St. Lawrence and 0°C on the Newfoundland and Labrador shelves. Comprehensive surveys in the Gulf since the mid-1980s (Fig. 5B), for example, have established trends in the thickness and volume of the CIL, with maxima in both features observed in the early 1990s and minima in more recent years (Gilbert et al. 2004). Similar patterns of expansion/contraction of the CIL have been observed in Newfoundland–Labrador waters and on the eastern Scotian Shelf. As is the case for bottom temperatures and the Thermal Habitat Index, the CIL is viewed as an oceanographic property (of the water column) of particular relevance to fish habitat issues and is also considered a robust index of ocean climate variability.

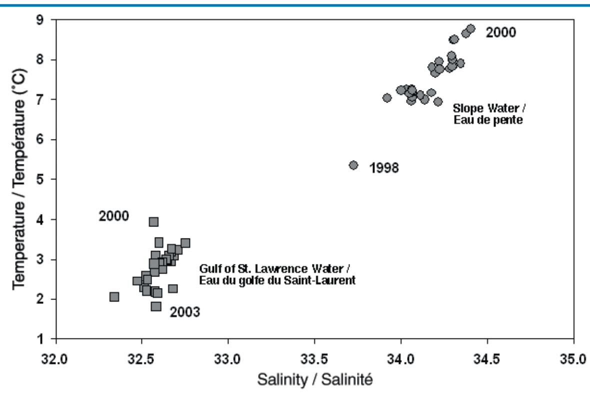

Fig. 6 Temperature and salinity characteristics of slope (circles) and subsurface Gulf of St. Lawrence waters (squares) from the July groundfish surveys on the Scotian Shelf between 1970-2003.

Caractéristiques de température et salinité des eaux de la pente continentale (cercles) et des eaux de sub-surface du golfe du Saint-Laurent (carrés) provenant des relevés de poissons de fond sur le plateau Néo-Écossais effectués en juillet entre 1970 et 2003.

Temperature and salinity data derived from these broad-scale surveys have also been used to define water masses and to quantify their contributions to regional hydrography. The mean temperature and salinity of slope water and subsurface Gulf of St. Lawrence water on the Scotian Shelf vary substantially from year to year (Fig. 6). On average, slope water makes up about 46% by volume of the total water on the Shelf; the Gulf water constitutes about 23%. The temperature and salinity vary over a range of about 2.1°C and 0.45 for the Gulf water and 3.4°C and 0.7 for the slope water. In 1998, slope water of Labrador Current origin dominated the deep Shelf waters. Waters of both types reached their highest temperatures in 2000. The waters from the Gulf were particularly cold in 2003, giving rise to a very extensive CIL on the Scotian Shelf throughout the year. Temperature and salinity profiles from these surveys have also been used to characterize the vertical density structure and establish spatial and temporal trends in the "Stratification Index" (difference in density between the surface and 50 m). Stratification is thought to play an important role in the exchange of nutrients between the surface and deep waters and in determining the vertical structure of phytoplankton population abundance and growth. Since 1990, the Scotian Shelf has been generally more strongly stratified than it had been in the previous 20 years. Fluorescence profiles collected from CTD casts aboard Maritimes groundfish surveys have been parameterized to characterize the vertical structure of phytoplankton, i.e., the background levels, depth, magnitude and vertical extent of the subsurface biomass maximum and the column-integrated total biomass (Fig. 7).

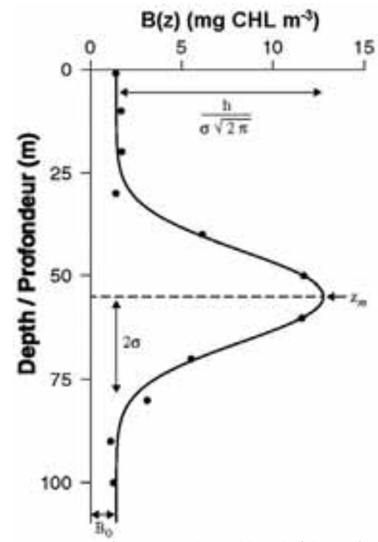

Fig. 7 Parameterization of the vertical profile of chlorophyll (CHL) using an offset Gaussian formulation. Four parameters are derived: the background chlorophyll concentration per m^3 (B_O), the depth of the subsurface chlorophyll maximum (Z_m), the vertical dispersion or width of the subsurface chlorophyll maximum (Sigma, σ), and the column-integrated chlorophyll concentration per m^2 (h) (Platt et al. 1988).

Paramétrisation des profils de chlorophylle (CHL) à l'aide d'une formulation Gaussienne balancée. Quatre paramètres sont dérivés : la concentration en chlorophylle de base du milieu par m^3 (B_O), la profondeur du maximum de chlorophylle sous la surface (Z_m), la dispersion verticale ou l'étendue du maximum de chlorophylle (Sigma, σ), et la concentration en chlorophylle intégrée sur la colonne d'eau par m^2 (h) (Platt et al. 1988).

These profile properties vary spatially over the Shelf and from year to year. Results from the July 2000 Scotian Shelf groundfish survey, for example, show the deepest fluorescence maxima occurring on the central Shelf and the shallowest in the eastern Gulf of Maine (Fig. 8A). Furthermore, fluorescence maxima on the inner Shelf were generally spread over a greater vertical depth range than outer Shelf profiles. Shelf-wide, the depth of the fluorescence peak was shallower and its vertical extent greater in 2001 than in previous or subsequent years (Fig. 8B). The vertical structure of phytoplankton may play an important role in their availability as food for planktonic grazers and grazer survival/growth.

A more recent application of oceanographic data derived from these surveys has focussed on establishing a link between the large-scale atmospheric forcing of the North Atlantic

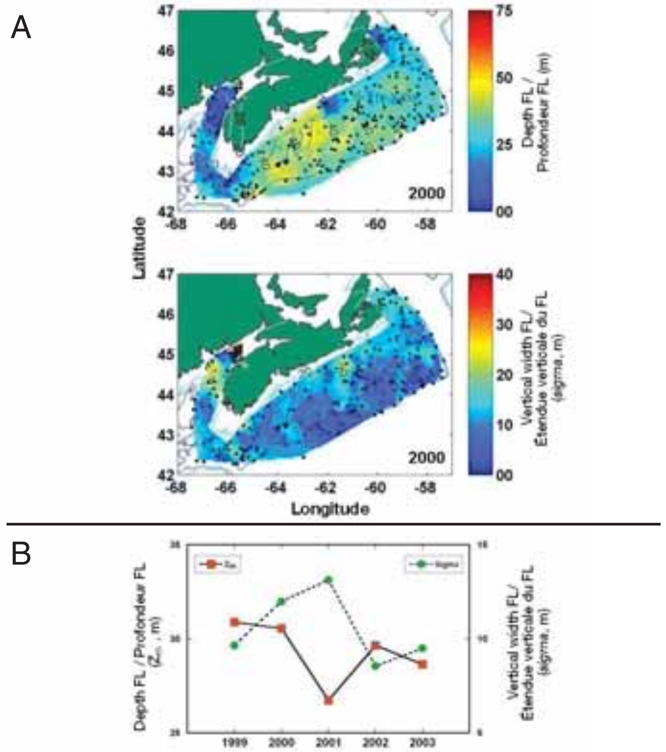

Fig. 8 (A) Contour plots of the depth (Z_m) and vertical width (sigma) of the subsurface fluorescence maximum (FL) on the Scotian Shelf during the annual July groundfish survey in 2000. (B) Year-to-year (1999-2003) variations in the shelf-wide mean depth and vertical width of the subsurface fluorescence maximum.

(A) Carte de la profondeur (Z_m) et de l'étendue verticale (sigma) du maximum de fluorescence (FL) en profondeur durant les relevés annuels de juillet de poissons de fond sur le plateau Néo-Écossais en 2000. (B) Variations interannuelles (1999-2003) de la profondeur moyenne sur tout le plateau et étendue verticale du maximum de chlorophylle en profondeur.

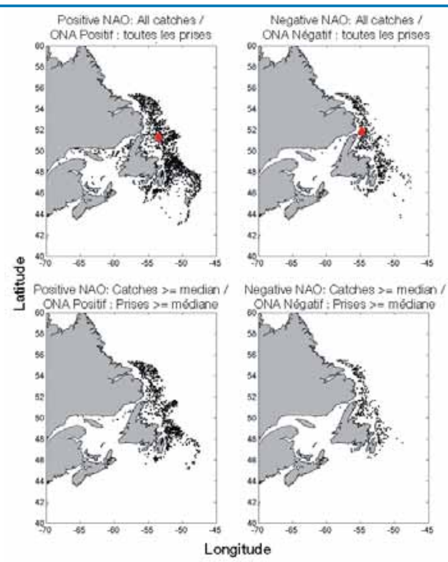

Fig. 9 Distribution of Arctic cod from DFO groundfish surveys in cold years (positive NAO anomalies) and warm years (negative anomalies) as defined by the NAO winter index. All catches are shown in the upper panels; catches that equaled or exceeded the median catch are in the lower panels.

Répartition de la morue Arctique à partir des relevés de poissons de fond du MPO durant les années froides (anomalies ONA positives) et chaudes (anomalies négatives) tel que déterminé par l'indice hivernal du ONA. Toutes les prises sont montrées dans les panneaux du haut; les prises qui excèdent la prise médiane sont montrées dans les panneaux du bas.

Oscillation (NAO) and fish habitat and distribution. Bottom temperatures over the Labrador–Newfoundland Shelf, in the Gulf of St. Lawrence and over the eastern Scotian Shelf are found to be significantly colder for years with positive NAO anomalies (cold winters) when two or more preceding years also had negative anomalies and vice versa. We expect then that catches of northern species from groundfish surveys during such positive NAO years would show movement southward. This is indeed the case for Arctic cod (Fig. 9), whose range increased from 122,000 km^2 in warm years to 249,000 km^2 in cold years. Other species show similar patterns, and we are examining a large number of them to determine how prevalent this response is.

International Activities

Internationally, the collection of oceanographic data on fisheries surveys and their use in stock assessment have been identified as essential elements in moving towards an ecosystem-based marine resource management framework. In its new Action Plan, the International Council for the Exploration of the Sea, ICES (www.ices.dk), has proposed a system-wide integrated monitoring network for member nations that incorporates oceanographic and fisheries data. The International Bottom Trawl Survey (IBTS) program (www.ices.dk/ocean/project/IBTS) is one example in the NE Atlantic where oceanographic data are collected and routinely reported along with fisheries data. This approach is also implicit in the function of the Northwest Atlantic Fisheries Organization's (NAFO) Standing Committee on Fisheries Environment (STACFEN) in which Canada plays a major role (www.nafo.ca/ activities/Frames/AcFrSci.html).

Implementing and sustaining oceanographic measurements on fisheries and other surveys require an ongoing commitment of resources. In the North Sea, for example, recent estimates suggest that the financial outlay for environmental/oceanographic observations represents less than 2% of the annual cost for integrated marine resource assessment (ICES 2003); the allocation of resources in Canada is probably similar. Sustaining oceanographic observations on fisheries surveys is also highly dependent on "buy-in" by assessment scientists and resource managers; this is secured by the development and use of relevant data products. As shown, AZMP is endeavoring to produce a broad spectrum of data products useful to both oceanographers and resource scientists/managers and is contributing to the international leadership role that Canada is taking in implementing the ecosystem approach to marine resource management.

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The Scotian Shelf Groundfish Trawl Survey

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Sommaire
Le relevé annuel des poissons de fond sur le plateau Néo-Écossais est exhaustif tant sur le plan spatial que temporel puisqu'il couvre le plateau Néo-Écossais dans son ensemble ainsi que la baie de Fundy, et qu'il a été effectué à chaque année depuis 1970. Quelques 6000 stations ont ainsi été échantillonnées avec succès. Ce relevé a généré des données précieuses sur l'abondance et la répartition des espèces commerciales aussi bien que sur les espèces non commerciales de poissons. Ce relevé comprenait un échantillonnage hydrographique (température et salinité) dont les objectifs ont récemment été étendus pour inclure l'échantillonnage des plus bas niveaux trophiques. Par exemple, depuis 1999 tous les macro-invertébrés benthiques ont été quantifiés. La présente revue touche quelques unes des nombreuses applications potentielles des données de relevés qui sont utilisées pour étudier la gestion des ressources, la biogéographie, ou encore les patrons de diversité des espèces de poissons.

Annual, standardized groundfish surveys of the Scotian Shelf were first implemented in the summer of 1970 and have continued uninterrupted to present. The surveys have assumed a key role in the provision of scientific advice for fishery management due to the many shortcomings of commercial fishing data, such as occasional poor accuracy, weak indicators of stock abundance, and the general lack of useful abundance estimates of incoming year-classes. The survey uses a random, stratified sampling design where the stratification is based on depth and the allocation of sets per stratum is proportional to stratum area (Fig. 1). Set location is based on a random selection procedure. The Scotian Shelf summer survey contains 48 strata distributed among four depth zones (< 50 fa, 51-100 fa, > 100 fa, mixed). The total number of sets per year has ranged from 115 to 212; since 1992, set number has been increasing. Throughout the history of the survey the gear has changed only once; this occurred in 1982, when the Yankee 36 trawl was replaced by the Western IIA trawl. Both gear types contained a small mesh liner capable of retaining forage and small, non-commercial species and young-of-the-year groundfish. A vessel change also occurred in 1982, when the *A. T. Cameron* was replaced by the *Lady Hammond*. In 1983, the newly commissioned *Alfred Needler* became the principal survey vessel. Comparative fishing experiments were conducted at the time of the vessel conversions and correction factors exist for a few of the dominant groundfish species (Fanning 1985). Otherwise, the vast majority of species collected and their estimated abundances represent a continuous series from 1970 to present. Hydrographic sampling has also been conducted on the survey since its inception and has contributed significantly to the regional database for the Scotian Shelf.

The surveys generate valuable data on the abundance and distribution of groundfish species. For many of the commer-

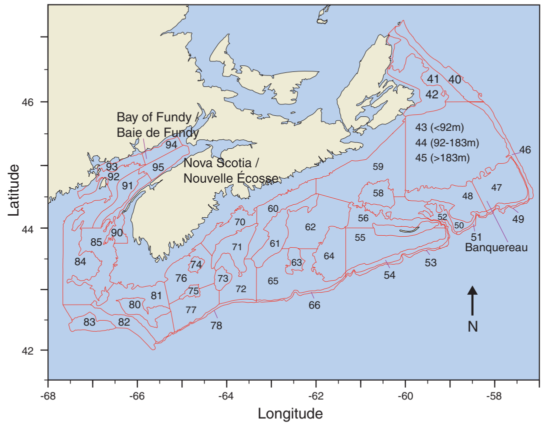

Fig. 1 Sampling design for the summer groundfish survey from a research vessel on the Scotian Shelf and Bay of Fundy. Strata are numbered from 40 to 66, corresponding to NAFO Division 4VW, and 70 to 95, corresponding to 4X.

Plan d'échantillonnage pour le relevé d'été de poissons de fond effectué par un navire de recherche sur le plateau Néo-Écossais et dans la baie de Fundy. Les régions d'échantillonnage numérotées de 40 à 66 correspondent aux divisions de l'OPANO 4VW et de 70 à 95 à la division 4X.

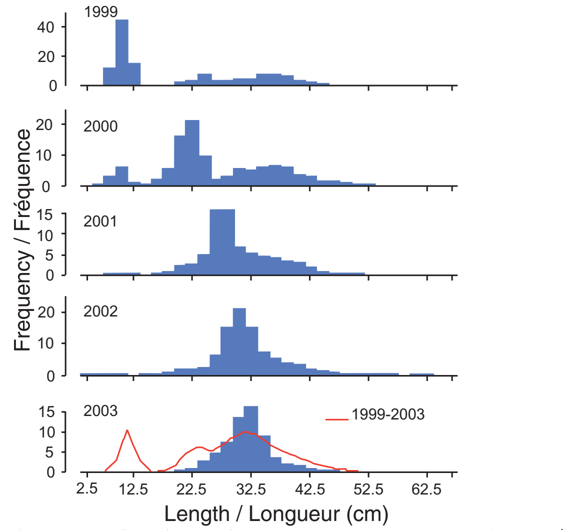

Fig. 2 Numbers at length for haddock from 1999 to 2003 in NAFO division 4VW showing the progression of year-classes in the stock.

Fréquence des classes de taille d'aiglefins pour la période 1999 à 2003 dans la division 4VW de l'OPANO montrant la progression des classes d'âge dans le stock.

cially important species, detailed biological sampling has been conducted for determination of age, maturity, feeding behaviour, and so on. Most of the survey information forms an important basis for analytical stock assessments, where age-specific survey abundance estimates are inter-calibrated with commercial fishery data through cohort analysis. The ability of the survey to track the progression of cohorts (or year-classes) has been repeatedly demonstrated (e.g., see Frank et al. 2001), and Figure 2 shows the progression of the 1999 year-class of haddock on the eastern Scotian Shelf from its birth year to age 4. In those instances where commercial fishery data are poorly resolved to the species levels (such as for flatfish and skates) and analytical assessments are not possible, the survey data provide the main foundation for fishery management advice. The same has been true for newly developing fisheries, where biomass estimates derived from the survey alone provide a baseline for management decisions.

One of the first ancillary uses of the survey data for purposes not directly related to stock assessment was the delineation of the closed area for haddock fishing that was established in 1987 on the central Scotian Shelf. The objective of the closure was to protect juvenile haddock from excessive discarding that typified the fishery during the early to mid-1980s and thereby allow the stock to rebuild. This industry-supported initiative utilized survey information on the distribution of juvenile haddock that existed at the time. Figure 3 shows the average abundance of age 1 and 2 haddock in 10-minute squares during the pre-closure period (1970-1986). The high concentrations of juveniles in the Emerald/Western banks region led to the establishment of the closed area in this region. Survey data have also figured prominently in the evaluation of this management measure (Frank et al. 2000).

The apparent colonization of capelin on the eastern Scotian Shelf was fully documented through the use of the groundfish survey database. The surge of capelin coincided with the occurrence of cold-water conditions that persisted for nearly a decade beginning in the mid-1980s. Prior to that time, few or no capelin were recorded from the area. In addition, several other cold-water species became abundant in the area coincident with capelin (Frank et al. 1996). Figure 4 shows the composite distribution of capelin from 1975 to 1985—a time when almost no capelin were encountered during the summer surveys—and from 1990 to 2000. During this latter period, maximum catch rates of capelin were four orders of magnitude higher than those recorded in the previous period. Recent data indicate a dramatic decline in capelin abundance coincident with an amelioration of water temperature conditions in the area.

The survey data are proving to be useful for the quantification of spatial and temporal patterns of species diversity and other related community-level analyses. This is possible because all of the species captured have been identified and

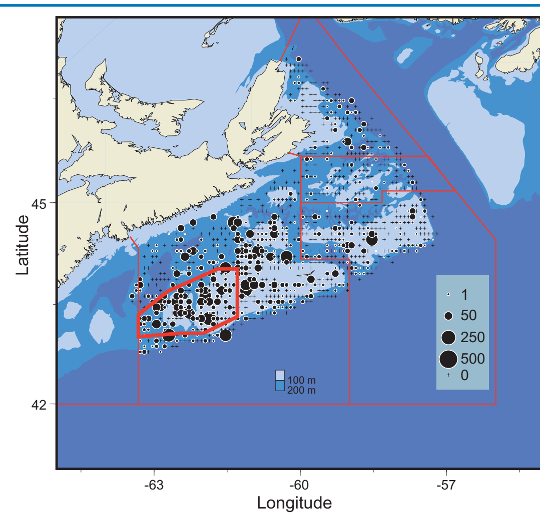

Fig. 3 Location of juvenile haddock (ages 1 and 2) from 1970 to 1986 in 4W. The location of the area closed to fishing (polygon) established in 1987 is shown encompassing Emerald and Western banks.

Position des juvéniles d'aiglefins (1 et 2 ans) pour la période 1970 à 1986 dans 4W. La position de la région fermée à la pêche (polygone) établie en 1987 comprend les bancs Emerald et Western.

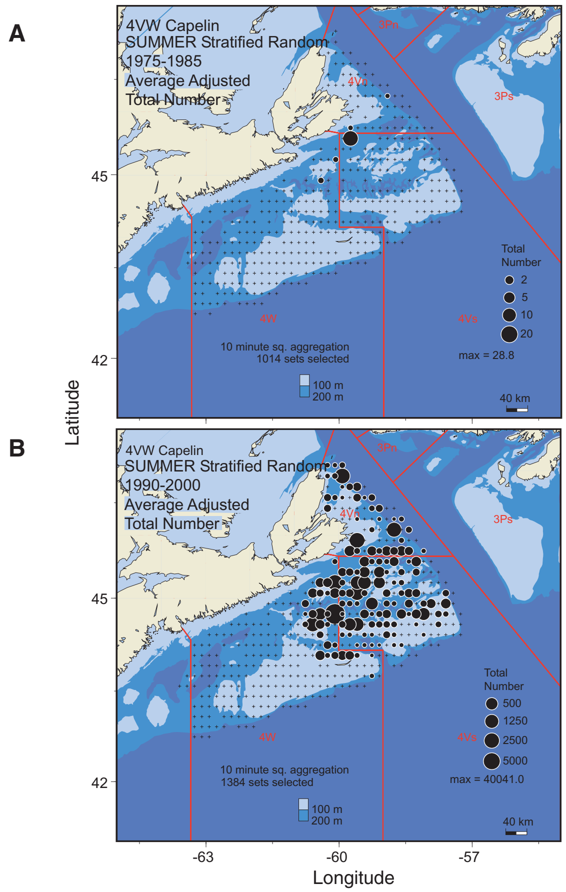

Fig. 4 Numbers of capelin per tow for the period (A) 1975-1985 and (B) 1990-2000.

Nombres de capelans par trait pour la période (A) 1975-1985 et (B) 1990-2000.

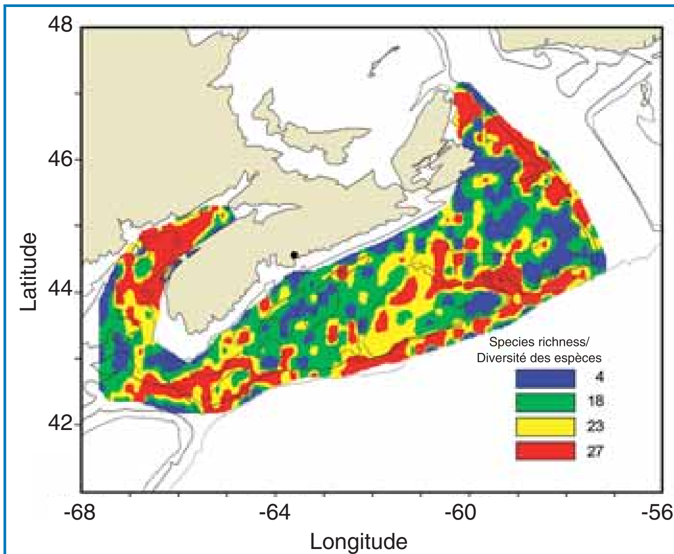

Fig. 5 Fish species richness based on the cumulative number of species from 1970 to 2002.

La diversité des espèces de poissons basée sur les nombres cumulatifs d'espèces entre 1970 et 2002.

enumerated since the inception of the survey. In only a few cases can resolution to the species level not be attained at sea (e.g., redfish). Groundfish species assemblages from the survey database were first examined by Mahon and Smith (1989), who used clustering methods of the catch-weighted species composition (for abundant species only) at the stratum level during four time periods to identify species associations in space and their persistence in time. Nine species groups and 10 site groups were defined that showed strong associations with depth and temperature gradients. More recently, Mahon et al. (1998) utilized survey data combined from several government laboratories to examine biogeographic patterns in species assemblages from Cape Hatteras to Cape Chidley. Many nations are now creating policy to conserve marine biodiversity, and diversity indices are much needed to monitor change and assess compliance with policy. Recent research (Shackell and Frank 2000) has been aimed at determining whether the groundfish survey could be used to monitor fish diversity and to determine the spatial patterns of diversity. The latter objective was based on an analysis of the cumulative number of species or species list, from 1970 to present, at a grid scale smaller than the strata as well as the stratum scale. Figure 5 shows the species richness on the Scotian Shelf at a 300-km^2 scale. Highly diverse areas include the Bay of Fundy, the eastern Gully, the slopes, Western Bank, and the northeastern Shelf. Until now, the northeastern Shelf has been under-appreciated as a highly diverse area because previous analyses were based on the number of species per tow rather than the cumulative number of species over time.

The survey data continue to be a basic research tool being utilized within DFO and by collaborators from several other research groups. It is among the best data series in existence for addressing questions dealing with the testing and development of ecological theory to its original intended use—providing timely fisheries management advice. This overview has provided just a few examples of the variety of ways this information has been used in the past.

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The Halifax Section: A Brief History

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Sommaire

L'historique du transect de Halifax remonte aux années 1930 quand Harry Hachey a initié des échantillonnages hydrographiques à grande échelle sur les côtes de la Nouvelle-Écosse. Ce transect a été formalisé en 1950 comme comprenant 7 stations situées entre l'isobathe de 80 m au large du port de Halifax, jusqu'à l'isobathe de 2500 m situé à 250 km plus au large sur le talus continental. Le but visé était une occupation saisonnière des stations de ce transect. On peut affirmer sans se tromper que notre connaissance de la structure des masses d'eau, des cycles annuels de température et de salinité, de la variabilité interannuelle, du mélange et de la circulation sur le plateau Néo-Ecossais a été principalement acquise à partir de la base de données hydrographiques existantes, la section Halifax représentant un contributeur majeur de cette base de données. Il ne faudrait pas oublier non plus que les personnes qui ont été impliquées dans la collecte, l'analyse et l'interprétation de ces données hydrographiques, notamment les Hachey, Lauzier, McLellan et Trites, représentent également une composante vitale qui a permis l'avancement de nos connaissances.

A Brief History

A series of seasonal cruises on the Scotian Shelf, starting near the coast off Halifax, progressing southward through Emerald Basin, over Emerald Bank to the 2500 m isobath on the continental slope, began in 1950. It became known as the Halifax Section and was occupied irregularly until the late 1970s. Sampling resumed in the early-to-mid 1990s and is ongoing. The Halifax Section was established in part because earlier, quasi-systematic sampling across the shelf, mainly in the 1930s, had built up a core hydrographic and limited dynamic picture of the physical oceanography along the transect (see, e.g., Hachey, 1938).

In the pre-1950 era, a significant amount of progress was made, particularly by Harry Hachey (Fig. 1), towards the understanding of water-mass structure and movement on the Scotian Shelf. For example, Hachey (1938) addressed the issue of the origin of the "cold water layer," later known as the cold intermediate layer or CIL (Fig. 2). He concluded that the layer was not formed in situ but originated outside the Scotian Shelf region to the northeast of the Halifax Section and was advected into the area. Hachey (1942) described the 3-layer hydrographic structure and its seasonal changes (Fig. 2). From 5 years of hydrographic data, he made geostrophic current and transport estimates over the shelf, including some estimates of seasonal variability (Hachey 1947; Fig. 3). He concluded that the transport to the southwest on the inner half of the shelf was strongest in winter and weakest in summer. Sampling on the current Halifax Section was re-established in 1950. As the time series increased, oceanographers began to address scientific issues dealing with shelf mixing, circulation, biological coupling, variability and long-term climate changes.

Fig. 1 Harry Hachey (1901-1985), pioneer Canadian physical oceanographer.

Harry Hachey (1901-1985), pionnier de l'océanographie physique au Canada.

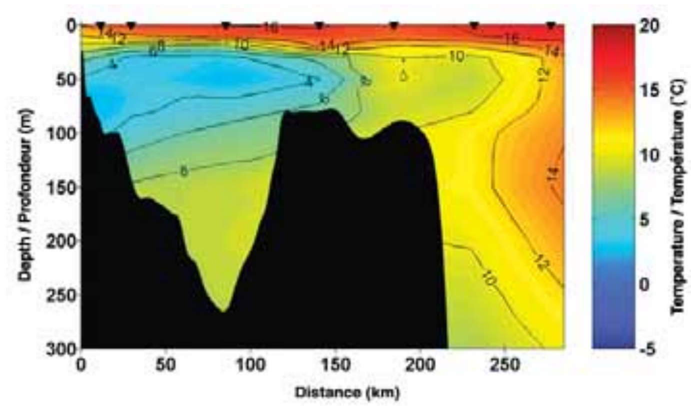

Fig. 2 Temperature section from 27-28 June 1999 along the Halifax Section (cruise 99022) showing the cold intermediate layer (CIL) and the three-layer structure on the inner half of the shelf. A thin surface layer with temperatures up to 16°C sits on the CIL (T<4°C). A layer of warmer, saltier water, which comes from the upper continental slope, lies underneath the CIL. The triangles at the surface indicate the station positions.

Profil vertical de la température pour les 27-28 juin 1999 le long du transect de Halifax, montrant la couche intermédiaire froide (CIF) et la structure en trois couches sur la partie interne du talus continental. À cet endroit, une mince couche de surface avec des températures jusqu'à 16 °C repose sur la CIF (T<4 °C). Une couche plus chaude et plus salée provenant de la partie supérieure du talus continental se retrouve sous la CIF. Les triangles en surface indiquent la position des stations d'échantillonnage.

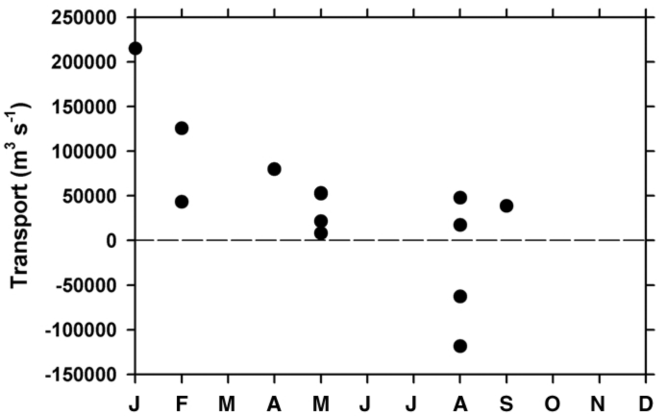

Fig. 3 Upper 30 m transport ($m^3 s^{-1}$) for the Nova Scotia Current (Hachey 1947). Southwest and northeast transport are positive and negative, respectively.

Transport ($m^3 s^{-1}$) *dans les 30 premiers mètres du courant de la Nouvelle-Écosse (Hachey 1947). Le transport vers le sud-ouest et le nord-est sont respectivement positif et négatif.*

McLellan (1954) examined along-shelf mixing from Banquereau Bank on the eastern Scotian Shelf to the Halifax Section. He quantified the changes in the proportions of 5 core water masses as they moved from east to west over the shelf using Halifax Section data as his anchor. Intrusions of offshore Slope Waters into the deep basin along the Halifax Line were observed to occur frequently, sometimes driven by horizontal density gradients and at other times by atmospheric storms (Hachey 1953, McLellan et al. 1953). Taylor (1961) presented the first 10 years of Halifax Section data as individual transects and updated this report in Taylor (1966); the next addition was by de la Ronde (1972), followed by Dobson (1975, 1977, 1978). Neither Taylor nor de la Ronde nor Dobson produced long-term means for the section. That was left to Drinkwater and Taylor (1982), who published the first section climatology, a collection of graphs and tables of the monthly mean temperatures, salinities and densities.

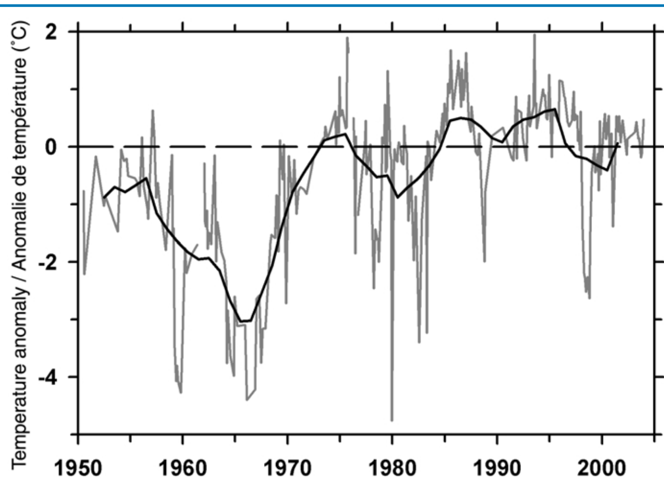

Fig. 4 Monthly (grey) and 5-year running mean filter of the annual (black) temperature anomalies in Emerald Basin. The 1971-2000 reference period was used to derive the long-term mean temperatures and the temperature anomalies.

Anomalies moyennes mensuelles de température (ligne grise) et anomalies filtrées sur 5 ans de la température annuelle (en noir) dans le basin Emerald. La période 1971- 2000 a été utilisée comme référence pour dériver la température moyenne à long terme et les anomalies de température.

As data were compiled and climatologies derived, understanding of the oceanography was growing, but some caveats were part of the story as well. Lauzier (1965) used section data to quantify a cooling trend on the Scotian Shelf that began in the early 1950s (Fig. 4). He noted that the trend was stronger on the outer shelf and suggested that a balance between Labrador Slope Water (LSW) and Warm Slope Water (WSW) was the cause of the low frequency climate variability. However, Mann and Needler (1967) concluded that seasonal sampling of the Halifax Section was inadequate to determine interannual variability. They maintained that short-term changes were large enough to contaminate year-to-year variations, i.e., the low frequency variability was "aliased" by the high frequency fluctuations. Mann (1969) used the data from 19 section occupations from February 1961 to April 1963 to describe the variability of LSW and WSW at the shelf edge. He reiterated the earlier warnings of Mann and Needler (1967) about aliasing arising from the infrequent sampling. The aliasing issue was a major factor in the abandonment of Halifax Section sampling in the late 1970s.

Nonetheless, considerable progress, resting on the foundation of the Halifax Section observations, was made in the 1970s on shelf processes, supporting the importance of existing monitoring data. Sutcliffe et al. (1976) tracked the freshwater outflow from the Gulf of St. Lawrence, quantified advection rates and patterns, and connected the CIL area to freshwater discharge; Fournier et al. (1977) estimated that cross-shelf exchange could supply enough nutrients to account for 20% of the annual primary production on the shelf; in addition, they tied the observed biological variability to physical property distributions on the section; Smith et al. (1978) linked wind forcing to slope water intrusions and inner shelf flushing; Houghton et al. (1978) quantified cross-shelf mixing of T, S and nitrate and related the mixing parameters to shelf-edge eddy fluxes; finally, Drinkwater et al. (1979) produced long-term monthly estimates of the along-shelf geostrophic transports and linked them to seasonal outflows from the Gulf of St. Lawrence (Fig. 5). Like Hachey (1947), they found the strongest transports to the southwest in winter and the weakest in summer.

A renaissance of Halifax Section data analysis and sampling emerged in the 1990s, largely driven by biological issues. Petrie and Drinkwater (1993) examined long-term variability in the Scotian Shelf–Gulf of Maine region for 1945-1990 (Fig. 4). They addressed

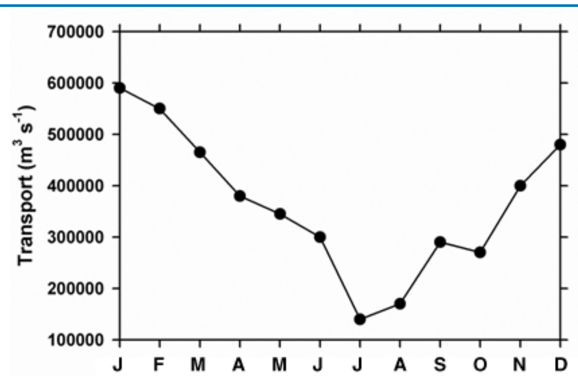

Fig. 5 Long-term, monthly transports ($m^3 s^{-1}$) over the entire Halifax Section, 0-100 m (Drinkwater et al. 1979). Transport is to the southwest in all months.

Transport mensuel moyen ($m^3 s^{-1}$) *au dessus du transect de Halifax en entier, 0-100 m (Drinkwater et al. 1979). Le transport est vers le sud-ouest pour tous les mois.*

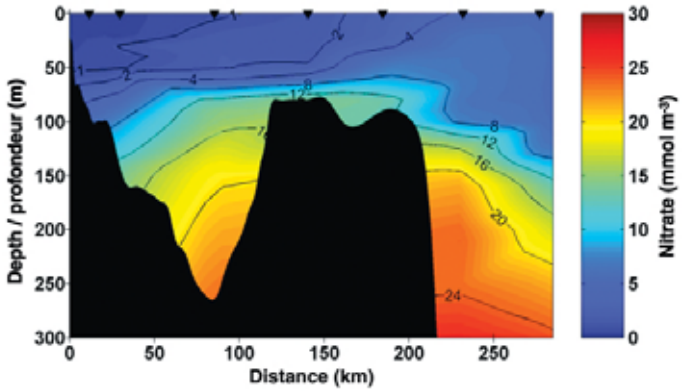

Fig. 6 Nitrate concentrations from 08-18 April 1999 along the Halifax Section (cruise 99003), showing depleted nitrate in the near surface and high concentrations over the slope and in the deep area of Emerald Basin.

Concentrations en nitrates entre les 08 et 18 avril 1999 le long du transect de Halifax (mission 99003), montrant l'épuisement des nitrates dans les eaux près de la surface et de fortes concentrations au dessus de la pente continentale et dans la couches profonde du basin Emerald.

the aliasing issue raised by Mann and Needler (1967) and found that the Halifax Section sampling was indeed sufficient to detect the longer-term hydrographic (temperature and salinity) trends, revived and modified the Lauzier hypothesis, and connected the hydrographic variability to cause through observations and modelling. In Emerald Basin (Stations 2, 3 of the Halifax Section), they found long-term temperature changes of 4-6°C depending on the depth (Fig. 4). Loder et al. (2001) used the section observations and a circulation model to contrast the cold and warm periods in the Scotian Shelf–Gulf of Maine region. In particular, they found that during the cold period, the southwestward transport in winter for the inner half of the shelf (Nova Scotia Current) was 400,000 $m^3 s^{-1}$, greater than for the same season in the warm period. Most recently, Loder et al. (2003) have addressed the nature of the ocean climate variability on the Scotian Shelf and found it to be episodic rather than continuous. This finding, in part, revives the concerns of Mann and Needler (1967), but focussed on transports rather than temperature and salinity, by showing that individual transport estimates from the section are aliased. They concluded, however, that there is the potential to monitor the Nova Scotia Current transport by using the Halifax Section data along with sea level and local winds. However, additional information, specifically adding more hydrographic stations to the Halifax Section, would be necessary over the continental slope.

Year-to-year descriptions and comparisons are still a part of the Halifax Section. The observations are used to describe the current oceanographic conditions for the international community (Drinkwater et al. 2003a) and for the Fisheries Oceanography Committee Workshops (Drinkwater et al. 2002). The AZMP monitoring documented the flushing of Emerald Basin by an intrusion of Labrador Slope Water in 1998, one of the most dramatic changes in the hydrography of the Scotian Shelf throughout the 1990s (Drinkwater et al. 2003b).

The history of the Halifax Section has been one of progress in the understanding of short- and long-term oceanographic variability. Imaginative oceanographers like Hachey, McLellan and Lauzier made use of limited amounts of data to address mixing processes, water mass formation and interannual variability. As the data set grew, hypotheses were refined, firmer connections to cause were made and our knowledge of the Scotian Shelf increased, especially of the interannual variability. While there is more to learn about the physical oceanography and the ocean climate of the Scotian Shelf from continuing monitoring of the Halifax Section, our greatest gains are likely to come in biology and chemistry, which have seen limited sampling in the past. The collection of nutrient and chlorophyll observations are now part of the regular AZMP sampling on the Halifax Section (Fig. 6, 7).

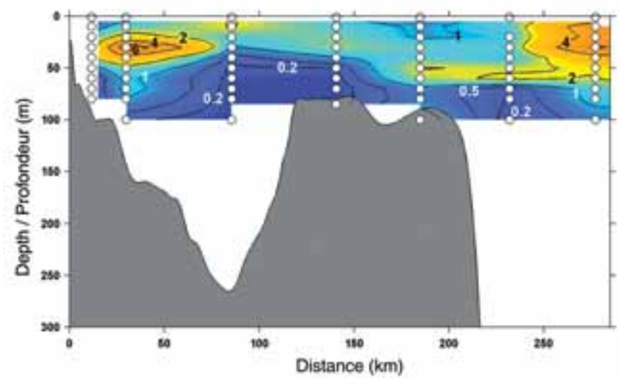

Fig. 7 Chlorophyll concentrations (mg m^{-3}) from 06-08 May 2001 along the Halifax Section, showing high subsurface concentrations on the inner shelf and a surface bloom over the slope.

Concentrations en chlorophylle (mg m^{-3}) *entre les 06-08 mai 2001 le long du transect de Halifax, montrant de fortes concentrations près des côtes et au dessus de la pente continentale.*

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The History of Standard Hydrographic Sections in Newfoundland and Labrador

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Sommaire

Le monitorage de la température et de la salinité le long de transects ou sections sur le plateau continental de Terre-Neuve et du Labrador a débuté en 1910 quand la Norvège a monté l'expédition de *Michael Sars* dans le nord-ouest de l'Atlantique. Entre 1913 et le milieu des années 1930, diverses expéditions internationales ont visité le plateau de Terre-Neuve et du Labrador et ont apporté une importante contribution à l'océanographie de cette région. Au cours de la période de fin 1940 et début 1950, un monitorage hydrographique standard a été implanté le long de plusieurs sections transversales sur les plateaux de Terre-Neuve et du Labrador tout d'abord par le Laboratoire de Recherche sur les Pêches de Terre-Neuve et, à partir de 1949, par la Station Biologique de Terre-Neuve sous l'égide de l'Office de Recherches sur les Pêches du Canada. Ce réseau de transects comprenait la section Seal Island au large de la région sud du Labrador, la section du Cap Bonavista, la section St. John's jusqu'au Bonnet Flamand, la section St. John's jusqu'à Southeast Shoal, la section banc Green jusqu'au sud-est de Grand Banc et la section du banc de St-Pierre jusqu'au sud-ouest du Grand Banc. Depuis ce temps, la Région de Terre-Neuve et du Labrador a continué l'échantillonnage de plusieurs de ces sections et a également ajouté d'autres sections dans son programme régulier de monitorage. Avant les années 1980, les données de ces transects étaient principalement utilisées par les chercheurs des pêches pour fournir une description annuelle de l'habitat du poisson et, occasionnellement, pour lier les variations observées de l'environnement physique aux changements observés dans les pêcheries locales. Vers le milieu des années 1980, quoique la description annuelle du climat océanique soit encore une priorité, il y a eu une utilisation accrue de ces données pour s'attaquer à des enjeux reliés aux échelles de variabilité, au changement du climat à long terme et la circulation locale. En 1993, dans le cadre du programme de recherche sur la morue du nord et depuis 1998 dans le cadre du programme de monitorage de la zone Atlantique (PMZA/AZMP), l'échantillonnage hydrographique le long des sections a été étendu pour inclure également des variables biologiques et chimiques. Plusieurs des transects sont échantillonnés sur une base saisonnière et les descriptions des conditions océanographiques basées sur ces données sont disponibles de façon routinière. Le monitorage futur le long des transects standard et des stations fixes devrait augmenter notre connaissance des processus physiques ainsi que des patrons à long terme du climat océanique et, peut-être encore plus significatif, devrait accroître notre compréhension des processus de l'écosystème en général.

Sampling History

Oceanographic observations on the Grand Banks of Newfoundland began as early as 1894, when Captain John Lewis reported surface and bottom temperature observations from the fishing schooner *Jubilee*. These were presented in the annual report of the Newfoundland Department of Fisheries for 1895. In 1910, the Norwegian *Michael Sars* expedition of the northwest Atlantic occupied two hydrographic sections across the northern and southern Grand Bank. In 1913, less than a year after the *Titanic* disaster, the British government along with several Atlantic steamship companies mounted the *Scotia* expedition under Dr. D. J. Matthews. This was the first systematic hydrographic study on the Grand Bank and waters adjacent to the Newfoundland Shelf and was the predecessor of the International Ice Patrol (IIP) of today. In

A

B

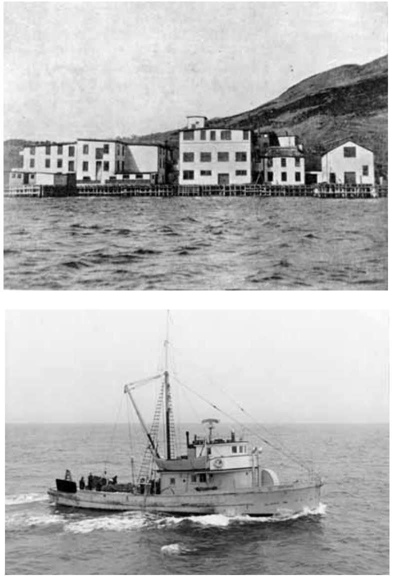

Fig. 1 (A) The Newfoundland Fisheries Research Commission's Bay Bulls research laboratory established in 1931. (B) The first full-time research vessel, the *Investigator II*, was commissioned in 1946 and operated until 1970.

*(A) Laboratoire de recherche de la Commission de Recherche sur les Pêcheries de Terre-Neuve établi dans Bay Bulls en 1931. (B) Le premier navire de recherche permanent, l'*Investigator II*, qui a été affrété en 1946 et qui a opéré jusqu'en 1970.*

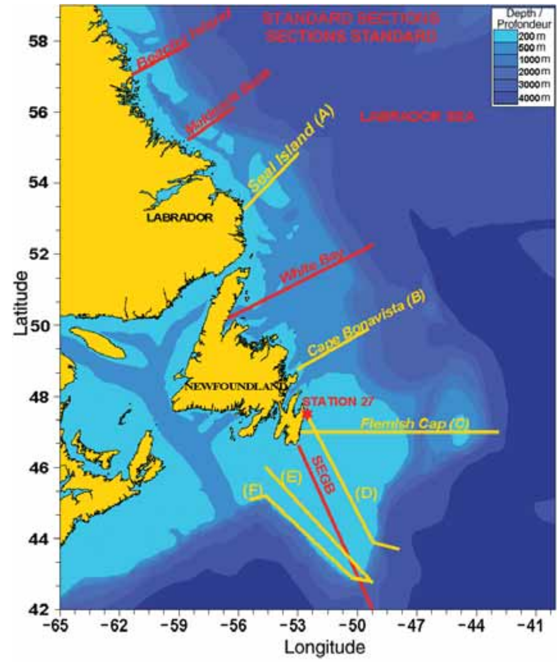

Fig. 2 Map showing standard sections and Station 27. The White Bay and Beachy Island sections were established by ICNAF (International Commission for the Northwest Atlantic Fisheries) in 1978. The sections A-F were standardized in the early 1950s by the Fisheries Research Board of Canada and the section SEGB was standardized by the AZMP in 1998.

Carte montrant la position des sections standard et de la Station 27. Les sections White Bay et Beachy Island ont été établies par le CIPAN (Commission internationale pour les pêcheries de l'Atlantique Nord-Ouest) en 1978. Les sections A-F ont été implantées au début des années 1950 par l'Office de recherche sur les Pêcheries du Canada et la section SEGB a été ajoutée par le PMZA en 1998.

1914, the United States Coast Guard initiated oceanographic observations on the Newfoundland and Labrador Shelf as part of its ice patrol services to monitor the Labrador Current and the transport of icebergs to southern shipping lanes. Hydrographic sections were also sampled on the Grand Banks by a Canadian Fisheries Expedition from 1914-1915. Its results laid the foundation for oceanography in Canada and provided one of the first textbooks on the theory and methods in oceanography (Hjort 1919). From 1925 to 1932, France carried out extensive hydrographic studies on the Grand Banks of Newfoundland in connection with the fishing industry. Numerous other international surveys of the waters of the northwest Atlantic were conducted in the decades following the first World War, including the *Chance* expedition on the Labrador Shelf in 1926, the German *Meteor* expeditions in 1928-1933, the British *Challenger* expedition in 1932 and the IIP *Marion* (1928) and *General Greene* expeditions (1931-1935); all occupied sections in the waters adjacent to Newfoundland and Labrador. Based on the *Marion* and *General Greene* surveys, Smith et al. (1937) published the first comprehensive study of the Labrador Current system, which even today is the classic reference for the oceanography of the Newfoundland and Labrador Shelf.

Systematic hydrographic sampling on the Grand Banks in support of fisheries research was initiated in 1931, when the Newfoundland Fisheries Research Commission opened its research laboratory at Bay Bulls, Newfoundland (Fig. 1A), under the directorship of Dr. H. Thompson. Temperature, salinity and drift-bottle data for a five-year period from 1931-1935 were collected by this laboratory at repeated stations in Newfoundland waters by the contracted trawler *Cape Agulhas*. The laboratory was destroyed by fire in April 1937. A new laboratory opened in St. John's in 1940, but it was not until the commissioning of the *Investigator II* as a full-time research vessel in 1946 (Fig. 1B) that hydrographic work resumed under the directorship of Dr. Wilfred Templeman. During the late 1940s and early 1950s, hydrographic monitoring along several sections crossing the Newfoundland and Labrador Shelf was initiated. After 1949, the St. John's laboratory was renamed the Newfoundland Biological Station under the Fisheries Research Board of Canada. Beginning in 1951, this laboratory standardized six hydrographic sections (referred to as sections A-F; Fig. 2) on the Newfoundland and Labrador Shelf that included (A) Seal Island Section, (B) Cape Bonavista Section, (C) St. John's to Flemish Cap Section, (D) St. John's to Southeast Shoal Section, (E) Green Bank to southeast Grand Bank Section, and (F) St. Pierre Bank to southwestern Grand Bank Section (Templeman 1975). The first sequential station of section (C) beginning immediately off St. John's Harbour was 27, which became a long-term monitoring station and was reported on in the previous AZMP bulletin (Colbourne and Fitzpatrick 2003).

Several countries of the International Commission for the Northwest Atlantic Fisheries (ICNAF) carried out oceanographic measurements along some of the standard sections as part of a larger northwest Atlantic monitoring program in support of fisheries assessments. In 1978, the Standing Committee on Research and Statistics of ICNAF standardized a series of sections and stations throughout the northwest Atlantic (Anon. 1978). Included in these were the historical sections (A, B and C; Fig. 2) that were established earlier in the region along with additional sections and stations. The Newfoundland Region, operating from its new laboratory—the Northwest Atlantic Fisheries Centre under the auspices of ICNAF and renamed the Northwest Atlantic Fisheries Organization (NAFO) in 1979—continued to sample the Seal Island, Cape Bonavista and Flemish Cap sections and the newly added White Bay Section among others on a regular basis, usually in mid-summer. Other sections in the region were sampled irregularly as requirements and resources permitted. In 1993, under the northern cod science program, and since 1998, under the AZMP, a version of the Southeast Grand Bank Section was restarted and sampled regularly. Under these programs, sampling along the sections was expanded beyond the regular physical measurements to include biological and chemical variables as well. Since the implementation of the AZMP, the southeast Grand Bank, Flemish Cap and Bonavista sections have been sampled seasonally while the rest, as mentioned above, are sampled during mid-summer.

Historically, most of the temperature and salinity data along the sections were collected at standard discrete sampling depths (0, 10, 20, 30, 50, 75, 100, 125, 150, 175, 200, 300, 400, 500, 600, 700, 800, 900, 1000 m) using oceanographic sampling bottles fitted with reversing thermometers. Since the mid-1960s, these samples were often supplemented with higher-resolution data collected using mechanical and electronic bathythermographs. Since the late 1970s, conductivity-temperature-depth (CTD) recorders, which measure water-mass properties very precisely at cm-scale depth intervals, have replaced the bottles and BTs.

Use of Data

In the 1930s, late 1940s and early 1950s, temperature and salinity observations from the hydrographic stations and sections were used mainly to provide annual descriptions of the shelf waters; occasionally, these were related to changes in local fisheries. The annual reports of the Newfoundland Fishery Research Laboratory for 1932 to 1936 and the proceedings of the North American Council on Fisheries Investigations (NACFI) contained brief descriptions of hydrographic conditions in Newfoundland Waters (NACFI 1935). The council in 1935 linked the abundance of cod in Newfoundland waters to temperature variations on the fishing grounds. The annual report of the Fisheries Research Board of Canada for 1950 contains the first detailed description of oceanographic conditions using standard section data (Templeman 1951). In that report, Templeman described seasonal variations in temperature with depth and attributed unusually large catches of cod and lobsters in shallow water and the greatest abundance of squid for many years in the Newfoundland area to the occurrence of warmer-than-usual surface waters. By 1952, enough data had accumulated to allow ICNAF, at its 3rd annual meeting, to hold a special session on long-term hydrographic changes and their effects on fish stocks in the northwest Atlantic (ICNAF 1953). Beginning in 1954, summaries of temperature and salinity variations along the standard sections were routinely included in the annual proceedings of ICNAF (Templeman 1955). As more data were collected, ICNAF initiated a series of special symposia on decadal reviews of environmental conditions in the northwest Atlantic. The first, held in Rome, Italy, in 1964, addressed the decade of the 1950s (ICNAF 1965); the most recent, in Dartmouth, NS, Canada, examined climate conditions in the northwest Atlantic during the 1990s (NAFO 2004).

A series of climatologies of temperature, salinity and density measured along several standard sections based on progressively longer time series have been published. Keeley (1981) produced the first analysis of the Flemish Cap Section using data from 1910 to 1980; Colbourne and Senciall (1996) extended it to include data from 1910 to 1995. Several other reports were published in the series Canadian Technical Reports of Hydrography and Ocean Sciences, including the Bonavista Section (Colbourne and Senciall 1993), the Seal Island Section (Colbourne et al. 1995) and the White Bay Section (Colbourne et al. 1999). The IIP has also conducted studies concentrated mainly in the offshore branch of the Labrador Current along the southeast slopes of the Grand Bank. Many other studies have included extensive analysis of temperature and salinity variability along the standard sections (e.g., Templeman 1975).

Petrie et al. (1988), using the standard section data along with Station 27 data, presented a comprehensive description of the Newfoundland Shelf temperature variability, specifically the cold intermediate layer or CIL, and concluded from correlation analysis that the spatial scales of variability are coherent over large areas of the Newfoundland Shelf. They then went on to describe in detail the spatial and temporal scales of variability in the temperature and salinity fields on the eastern Newfoundland Shelf (Petrie et al. 1992). A detailed study of the Labrador Current system was initiated in 1977 by the Bedford Institute of Oceanography (BIO) and continued until 1987 to estimate the annual and interannual variations in the properties of the Labrador Current using standard section data and moored current meters (Lazier 1982, Lazier and Wright 1993). Colbourne et al. (1997) examined the hydrography and circulation on the Newfoundland Shelf during the cold period

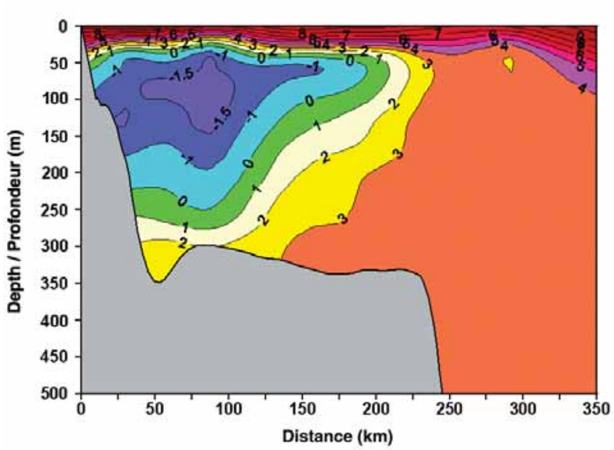

Fig. 3 A typical cross section of summer temperature conditions (˚C) along the standard Cape Bonavista Section.

Un profil transversal typique des conditions estivales de température (˚C) le long du transect standard du Cap Bonavista.

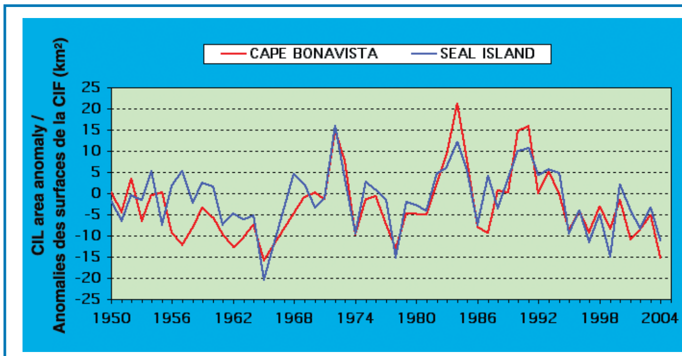

Fig. 4 Annual mid-summer cross-sectional CIL (< 0˚C) area anomalies along the Cape Bonavista and Seal Island sections. Anomalies are referenced to the 1971-2000 period.

Anomalies des surfaces transversales occupées par la CIF (< 0˚C) au milieu de l'été le long des transects Cap Bonavista et Seal Island. Les anomalies sont référencées à la période de 1971 à 2000.

of the early 1990s. Drinkwater (1996) and Colbourne et al. (1994, 2004) examined inter-decadal climate changes in the northwest Atlantic. Numerous other studies have used section data to examine environmental influences on growth, recruitment and distribution of many marine organisms in Newfoundland waters (e.g., Helbig et al. 1992, Shelton et al. 1999, Parsons and Lear 2001, Colbourne and Anderson 2003). These and other studies have contributed greatly to our understanding of the oceanography on the Newfoundland and Labrador Shelf and the linkages between ocean climate variability and the marine ecosystem.

A most revealing feature of the temperature structure on the Newfoundland and Labrador Continental Shelf is the layer of cold (<0˚C) water, commonly referred to as the Cold Intermediate Layer (Fig. 3). This cold, relatively fresh (salinities of 32-33) sub-polar water mass often extends offshore to the edge of the continental shelf. The combined effects of seasonal air–sea heat fluxes, intense winter convection and summer shelf stratification are the primary physical mechanisms leading to the formation of this water mass. The CIL index based on its cross-sectional area is a robust measure of ocean climate variability and is often used in descriptions of the environmental conditions in the region. The variability of the CIL is highly coherent on the Newfoundland and Labrador Shelf. Moreover, its area also shows considerable variability, with the difference between the maximum and minimum observed areas representing a change in layer thickness of approximately 100 m across the Bonavista Section (Fig. 4).

The climatologies and year-to-year descriptions dominated the use of the standard section and fixed station data until the mid 1980s. Moreover, annual descriptions of ocean climate that began in 1954 for ICNAF and presently for NAFO are still a primary focus and are perhaps one of the longest series of documentation available anywhere pertaining to ocean climate conditions in the North Atlantic (Colbourne and Fitzpatrick 2002). Beginning in the mid 1980s, there has been increasing use of the data to address issues related to scales of variability, long-term climate changes and circulation. During the mid 1990s, oceanographers from Canada began active participation in the ICES Oceanography Committee and its working groups and, using the section data time series, have contributed to the annual ocean climate status summary for the North Atlantic (ICES 2003). National and zonal groups, such as the Fisheries Oceanography Committee (FOC) of Fisheries and Oceans and the regional resource assessment proceedings (RAP), remain primary users of the standard section data (Colbourne 2003).

Standard Sections and the AZMP Era

In 1992, under the northern cod science program, limited biological sampling was initiated at Station 27 and along selected standard sections but ended with the termination of the program in 1995. Since 1998, as part of the Atlantic Zone Monitoring Program, biological and chemical sampling has resumed along the sections. Under this program, sampling has been expanded beyond the regular physical measurements to include dissolved oxygen, primary and secondary production and biomass, species composition of phytoplankton and zooplankton, and nutrients. Several of the sections are sampled on a seasonal basis (spring, summer and autumn), and physical, chemical and biological state-of-the-ocean reports are now routinely published from the data (Colbourne and Fitzpatrick 2002, Pepin et al. 2003). With seven years of continuous biological and chemical observations along some of the sections, investigators are now beginning to construct short-term mean conditions, similar to what was done with hydrographic observations throughout the 1950s. Continued monitoring along these sections and at fixed sites like Station 27 will greatly increase our understanding of physical processes and long-term trends in ocean climate. More significantly, however, the AZMP will allow a greater understanding of changes in ecosystem productivity and structure over time. It is in this area of research that the most significant contribution to ocean science will likely be made in the near future.

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Evidence of Enhanced Biological Productivity in Flemish Cap and Slope Waters Compared With the Adjacent Grand Banks

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Sommaire

La dynamique saisonnière des sels nutritifs et des populations de phytoplancton et de zooplancton est décrite le long d'un transect océanographique traversant les Grands Bancs à partir de la côte est de Terre-Neuve jusqu'au Bonnet Flamand (Flemish Cap) (centré autour de 47°N et 45°O). Les eaux moins profondes au dessus du Bonnet Flamand sont influencées par la proximité des circulations océaniques à grande échelle du courant du Labrador (LC) et du courant nord Atlantique (NAC) qui génèrent autour du Bonnet Flamand une gyre anti-cyclonique, des températures plus élevées et un entraînement des eaux riches en sels nutritifs du NAC. Ce processus de circulation fournit un avantage pour les producteurs primaires et secondaires dans la région du Bonnet Flamand par comparaison à la région du plateau des Grands Bancs. L'écoulement vers le sud du courant du Labrador à travers la passe du Bonnet Flamand et le long de son flanc nord, transporte, dans les eaux du Bonnet Flamand et dans celles de la pente continentale, des espèces subarctiques provenant des régions plus nordiques. Les concentrations accrues en sels nutritifs observées sur le Bonnet Flamand et dans les eaux de la pente continentale supportent alors des niveaux potentiellement plus élevés de production primaire (nouvelle production) qui résultent vraisemblablement en une production secondaire significativement plus élevée pour cette région en comparaison avec les régions adjacentes du plateau des Grands Bancs. Les estimés de biomasse obtenus pour les genres dominants de copépodes à partir des données du PMZA (CPR et échantillonnages par filets) supportent cette suggestion. La variabilité interannuelle dans la productivité primaire et secondaire et sa dépendance sur la dynamique des sels nutritifs et sur les mécanismes de transport au dessus du Bonnet Flamand demeurent des sujets de recherche continues pour le PMZA.

The Flemish Cap, located east of the Grand Banks of Newfoundland and centered at 47° N and 45° W (Fig. 1), is thought to have high primary and secondary productivity, which in turn support the abundant invertebrate and fish populations found in this area. The primary and secondary production cycles on the Flemish Cap are known to be seasonal (Anderson 1990), yet few studies have investigated the basis for enhanced productivity and interannual variability in the standing stocks of the lower trophic levels in this area. Two major current systems dominate the circulation and water-

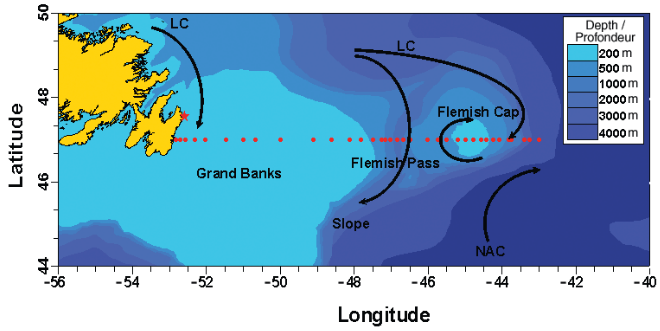

Fig. 1 Map of the oceanographic section across the Grand Banks Shelf, Flemish Cap and Slope waters showing sample station locations (red dots) along with the general bathymetry and circulation. The location of the inshore fixed coastal station (Station 27) is shown by the red star. The general locations of the inshore and offshore portion of the Labrador (LC) and North Atlantic (NAC) currents and the anticyclonic gyre that forms around the Flemish Cap are provided.

Carte du transect océanographique traversant les eaux du plateau des Grands Bancs et du Bonnet Flamand montrant la localisation des stations d'échantillonnage (points rouges) ainsi que la bathymétrie et la circulation générale. La localisation de la station fixe (Station 27) est montrée par l'étoile rouge. Les localisations générales des parties côtières et hauturières du courant du Labrador (LC) et du courant de l'Atlantique nord (NAC), et la gyre anticyclonique qui se forme autour du Bonnet Flamand sont également illustrées.

mass properties around the Flemish Cap (Colbourne and Foote 2000) (Fig. 1). The Labrador Current (LC) flows southward through the Flemish Pass and east and southeast around the northern and eastern slopes, transporting cold, low salinity Labrador Slope water onto the Cap. The circulation over the Cap is dominated by an anticyclonic gyre. The northward flowing North Atlantic Current (NAC) transports warmer, high salinity water to the northeast along the southeast slope of the Grand Banks and the Cap. The close proximity of the NAC to the Flemish Cap, with water temperatures in excess of 4°C, suggests mixing of the two current water masses, resulting in warmer waters and elevated nutrients on the Cap in contrast to the Grand Banks Shelf (Colbourne and Foote 2000). Variations in the physical and chemical environment are thought to influence the biological production and distribution of organisms in Newfoundland and Labrador Shelf and Slope waters, given the overlap between arctic, boreal, and temperate species. On a physiological basis, the elevated temperatures on the Cap, as a result of relatively ice-free conditions, may allow longer growing seasons and permit higher growth rates of primary and secondary producers as compared to the cooler conditions prevailing on the Grand Banks (GB) and along the western Slope.

The supply of nutrients to the euphotic zone is of importance to autotrophic organisms, principally phytoplankton, that form the base of the food chain for planktonic and benthic heterotrophs. The nutrients utilized by phytoplankton are predominately formed at depth through microbial processes and transported back to the photosynthetically active part of the water column by physical processes such as tidal and wind-induced vertical mixing, winter overturning and other upwelling processes. In certain regions, advection of nutrient-rich surface waters might be of greater importance than local surface nutrient replenishment processes.

Significant differences in the thermohaline properties and the distribution of inorganic nutrients are apparent across the Flemish Cap section during three sampling periods (Fig. 2). The seasonal occupations of the section show elevated temperature, salinity, and nitrate concentrations over the Cap and adjacent Slope waters in contrast to lower salinity, temperature, and nitrates on the Shelf. Despite the apparent higher nutrient levels over the Flemish Cap and in Slope waters during the spring occupation, the distribution of phytoplankton biomass as determined from chlorophyll *a* concentrations was largely confined to the Shelf. The location of the LC in the Flemish Pass region showing sharp thermohaline gradients marks the boundary between water masses on the Shelf and Flemish Cap. The thermohaline properties over the Flemish Cap suggest entrainment of North Atlantic water as the likely mechanism for nutrient enhancement in this region. Additional contributions of nutrients through vertical advective and mixing processes linked to the geostrophic flow of major current systems surrounding this region may also be important (see Yentsch 1980, Loder et al. 1988, Han 2004).

Relative changes in the nitrate and silicate pools in the Cap and Slope waters indicate a 10-fold reduction in concentrations during the transition from spring to sum-

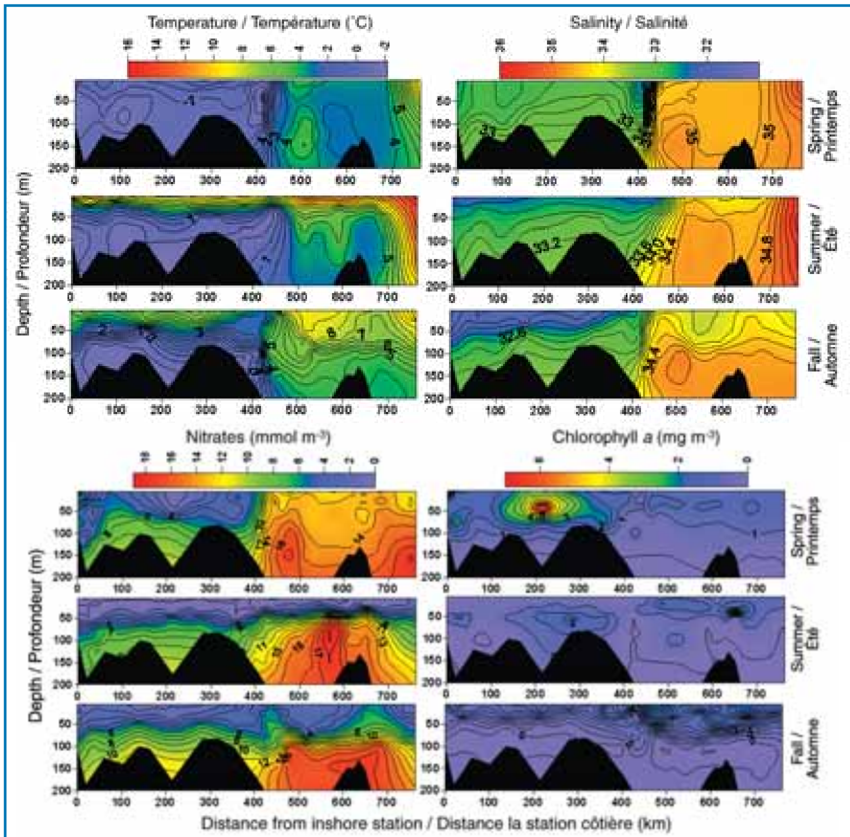

Fig. 2 Seasonal vertical profiles of temperature, salinity, nitrate (nitrate + nitrite combined) and chlorophyll *a* in the upper 200 m versus distance from the coastal station across the Flemish Cap section during 2003. Bottom bathymetry is shown in solid black.

Profils verticaux saisonniers de température, salinité, nitrates (nitrates et nitrites combinés) et chlorophylle a *dans les premiers 200 m versus la distance de la côte à partir de la station côtière traversant le Bonnet Flamand au cours de 2003. La bathymétrie du fond est indiquée en noir.*

Table 1 Seasonal averages (± SD) of integrated (0-75 m) nutrient and chlorophyll *a* inventories from 1996 to 2003 in waters of the Grand Bank Shelf (GBS), Flemish Cap (FC) and Slope (SL). The nitracline, defined as the depth at which the nitrate concentration exceeds 0.5 mmol m^{-3}, forms prominently during the summer stratification maximum.

Moyenne saisonnière (± ET) des inventaires intégrés (0-75 m) de sels nutritifs et de chlorophylle a *pour la période 1996-2003 dans les eaux le long du plateau des Grands Bancs (GBS), celles du Bonnet Flamand (FC) et celles de la pentes continentale (SL). La nitracline, définie comme la profondeur à laquelle la concentration en nitrates excède 0.5 mmol m^{-3}, se forme principalement durant la période de stratification estivale maximale.*

Season / Saison	Location / Position	Avg./Moy. NO_3 (mmol m^{-2})	Avg./Moy. SiO_4 (mmol m^{-2})	Avg./Moy. Chl *a* (mg m^{-2})	Nitracline (m)
Spring / Printemps	GBS	214.9 ± 96.0	193.5 ± 135.2	230.5 ± 139.4	
	SL	520.1 ± 137.6	434.8 ± 105.5	149.0 ± 99.3	
	FC	455.1 ± 142.7	427.6 ± 134.6	166.7 ± 97.7	
Summer / Été	GBS	199.1 ± 58.9	162.5 ± 85.7	53.1 ± 53.6	48.5 ± 8.7
	SL	349.7 ± 165.3	192.8 ± 74.3	70.8 ± 34.8	31.7 ± 8.1
	FC				
Autumn / Auomne	GBS	270.1 ± 64.5	334.9 ± 103.3	35.4 ± 18.4	
	SL	340.3 ± 81.2	214.3 ± 75.4	48.9 ± 20.2	
	FC	314.5 ± 58.5	199.5 ± 70.9	76.4 ± 50.3	

mer compared to those observed on the GB Shelf (Table 1). The large difference in inventories during this seasonal transition would suggest substantially higher overall production on the Cap and Slope compared to the GB Shelf. Although this could also reflect previous biological uptake by phytoplankton on the Grand Banks prior to the spring sampling period, we cannot rule out the relative contribution of water mass exchange through horizontal and vertical fluxes.

If we assume the average winter value of 300 mmol m^{-2} for the nitrate inventory obtained from Station 27 as a proxy for conditions on the Grand Banks, this suggests that some limited biological uptake has occurred prior to sampling. The seasonal and interannual variabilities in the nitrate and chlorophyll *a* inventories across the Flemish Cap section suggest that differences observed in recent years have been relatively consistent since the mid 90s (Fig. 3). One notable exception was the elevated nitrate inventories observed in the Slope waters and Flemish Cap during the spring and summer occupations in 1997 compared to the Grand Banks Shelf. The mechanism

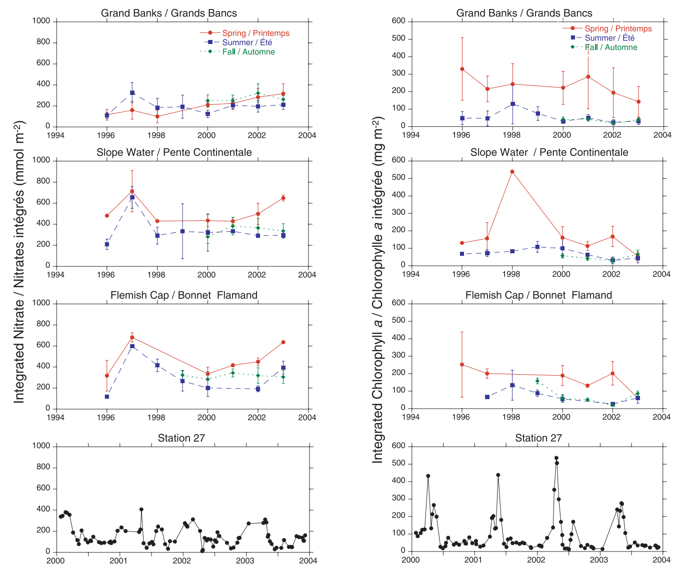

Fig. 3 Seasonal and interannual variabilities in nitrate (nitrate and nitrite combined) and chlorophyll *a* inventories across the Flemish Cap section from 1996 to 2003. Note that data are not available during some seasons and years for both nitrate and chlorophyll *a*. Bottom panels show the seasonal and interannual variability in nitrate and chlorophyll *a* inventories from the inshore fixed coastal station (Station 27) during bi-weekly monitoring from 2000 to 2004.

Variabilité saisonnière et interannuelle des nitrates (nitrates et nitrites combinés) et de la concentration intégrée en chlorophylle a *le long du transect du Bonnet Flamand pour la période 1996-2003. Noter que les données ne sont pas disponibles pour certaines saisons et années autant pour les nitrates que pour la chlorophylle* a*. Les deux figures du bas montrent la variabilité saisonnière et interannuelle des nitrates et de la chlorophylle* a *à la station fixe côtière (Station 27) pendant l'échantillonnage au deux semaines de 2000 à 2004.*

responsible for this nutrient enhancement in the Slope waters and Flemish Cap during 1997 is unknown but may be in part related to the variability in volume transport of the large-scale oceanic circulation in this region. Variability in the Labrador Current as determined by satellite altimetry data indicated intensification over the Newfoundland Slope from 1996 to 1997 (Han 2004).

Ocean colour images obtained from SeaWiFS over the NW Atlantic indicate that surface blooms occur throughout the spring and early summer (June-July) in the vicinity of the Flemish Cap whereas blooms on the Shelf are of limited duration (e.g., early May period; data not shown, but see http://www.mar.dfo-mpo.gc.ca/science/ocean/ias/remotesensing.html). Earlier studies have demonstrated that the spring phytoplankton bloom develops later on the Flemish Cap compared to the GB Shelf (Anderson 1990), although recent satellite data suggest that differences in the initiation of the spring bloom are not readily apparent in

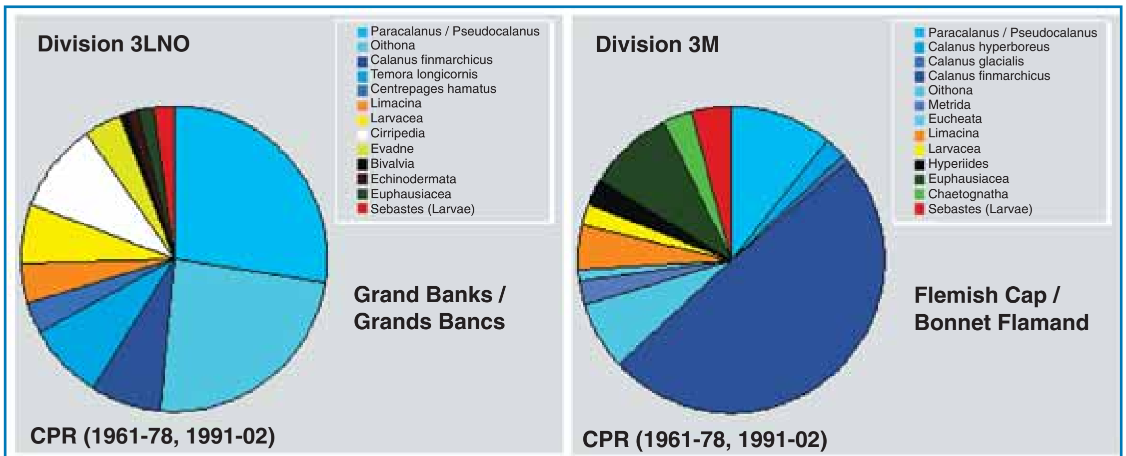

Fig. 4 Percentage contribution of major zooplankton genera enumerated by the Continuous Plankton Recorder (CPR) Program on the Grand Banks Shelf in NAFO Divisions 3LNO and Flemish Cap in NAFO Division 3M.

Contribution en pourcentage des genres majeurs de zooplancton énumérés par le « Continuous Plankton Recorder » (CPR) programme sur le plateau des Grands Bancs dans les divisions 3LNO de l'OPANO et sur le Bonnet Flamand dans la division 3M.

Table 2 Seasonal averages (± SD) of the stratification index (SI; density difference between 5 and 50 m divided by depth) and mixed layer depth (MLD; determined from the depth of the maximum gradient) from 2000 to 2004 along the Grand Bank Shelf (GBS), Flemish Cap (FC) and Slope (SL).

Moyenne saisonnière (± ET) de l'index de stratification (SI ; différence de densité entre 5 et 50 m divisé par la profondeur) et la profondeur de la couche de mélange (MLD ; déterminée à partir de la profondeur du gradient maximum) dans les eaux le long du plateau des Grands Bancs (GBS), sur le Bonnet Flamand (FC) et le long de la pente continentale (SL) au cours de 2000-04.

Season / Saison	Location / Position	Avg./Moy. SI ($kg\ m^{-4}$)	Avg./Moy. MLD (m)
Spring / Printemps	GBS	0.003 ± 0.002	64.3 ± 15.2
	SL	0.003 ± 0.002	57.9 ± 15.0
	FC	0.001 ± 0.001	75.4 ± 16.7
Summer / Été	GBS	0.034 ± 0.003	15.6 ± 2.6
	SL	0.035 ± 0.006	16.4 ± 1.7
	FC	0.031 ± 0.006	15.6 ± 2.3
Autumn / Auomne	GBS	0.018 ± 0.007	44.1 ± 2.4
	SL	0.008 ± 0.005	65.7 ± 16.9
	FC	0.007 ± 0.004	75.4 ± 10.4

some years. As revealed by the 1996-2003 mean, the depth of the nitracline shoals extensively in Slope waters and over the Cap compared to deeper depths on the Shelf (Table 1). Nitrate inventories also differ during the transition from summer to autumn, when nutrient replenishment is greater on the Shelf compared with the small changes on the Cap and Slope (Table 1). This might indicate that a small but significant level of primary production continues on the Cap and Slope versus lower rates on the GB Shelf. Similar nutrient gradients have been documented on the Scotian Shelf and in the Gulf of Maine and have been linked to several factors including the timing of the production cycle, enhanced vertical supply of nutrients through mixing or upwelling processes, inadequate sampling during winter, and advective export sources (Petrie and Yeats 2000).

Indices of stratification (SI) and mixed layer depth (MLD) vary seasonally across the Flemish Cap section. The seasonally averaged values of the SI are relatively low (0.001-0.003 kg m^{-4}) across the section during spring, although the higher values observed in the Shelf and Slope waters suggest stratification begins earlier than on the Flemish Cap (Table 2). The onset of earlier stratification on the Shelf may in part regulate the timing of the spring bloom across the section. The depth of the mixed layer deepens by 25% on the Flemish Cap (i.e., 75 m), compared to a value of about 60 m observed on the Shelf and Slope during the early production cycle. Assuming the depth of the euphotic zone is constant across the section, the shallow mixed layer observed on the Shelf during spring will also favour the occurrence of phytoplankton blooms. The SI increases by an order of magnitude during summer to 0.03-0.04 kg m^{-4} while the MLD shallows to about 16 m with little variability evident across the section. While the level of stability as measured by the SI remains relatively high from the summer into the autumn period on the Shelf, a more extensive breakdown of water column structure is observed on the Flemish Cap and Slope waters (Table 2).

Changes in the community composition along with associated differences in the numerical abundance and biomass of zooplankton were evident across the section. Combined data from the Continuous Plankton Recorder (CPR) surveys during the periods 1961-1978 and 1991-2002 indicate the numerical dominance of copepods over the Shelf and Flemish Cap (Fig. 4). However, many of the dominant species on the GB were substantially smaller in body size relative to the species found on the Flemish Cap. The AZMP monitoring data on the Flemish Cap Section in 2003 indicate that although the numerical abundance of the cyclopoid copepod *Oithona* sp. is high on the Shelf, the importance of the large Calanoid genera becomes evident when one sees how it dominates the biomass pattern across the entire Flemish Cap section (Fig. 5). During spring, the subarctic species *C. hyperboreus* and *C. finmarchicus* clearly dominate the biomass from the outer Shelf and across the Cap and Slope waters (Fig. 5). The other large Calanoid, *C. glacialis*, appears to be largely confined to the Shelf along with the smaller copepods *Pseudocalanus / Paracalanus* and *Oithona* sp. During summer, small copepods

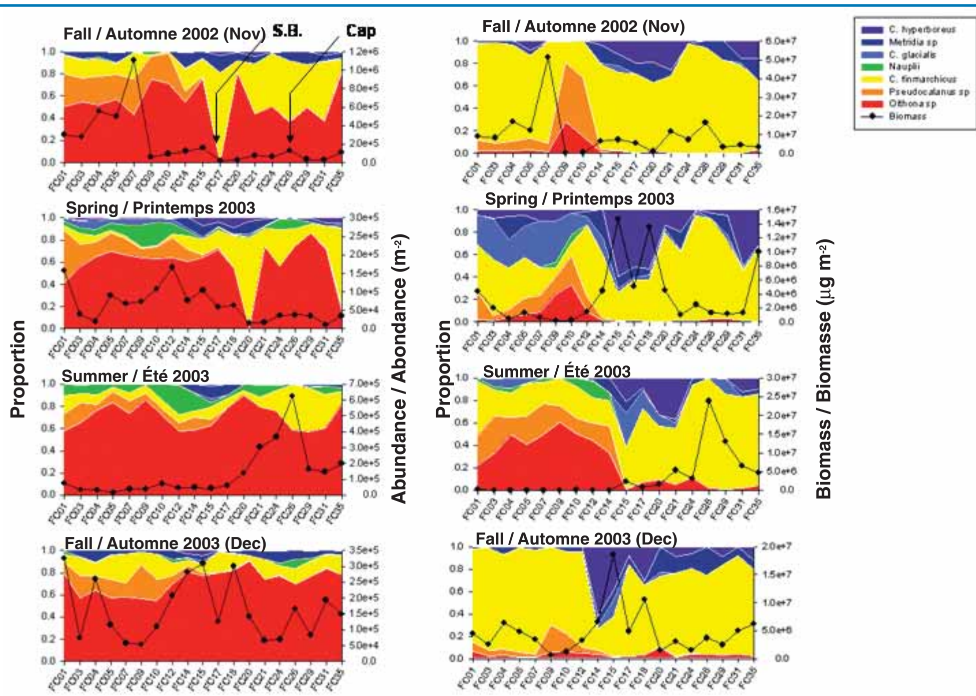

Fig. 5 Numerical abundance and biomass of major copepod genera from AZMP integrated vertical net tows along the Flemish Cap oceanographic section from 2002 to 2003. The approximate locations of the Shelf Break (S.B.) and the centre of the Flemish Cap (Cap) are provided.

Abondance numérique et biomasse des genres majeurs de copépodes obtenue à partir de données de traits verticaux du PMZA le long du transect océanographique du Bonnet Flamand en 2002-2003. Les positions approximatives de la rupture de pente (S.B.) et du centre du Bonnet Flamand (Cap) sont également indiquées.

make up a large proportion of the assemblage over the Shelf, but peak biomasses are found over the Cap and are dominated by bigger species such as *C. finmarchicus* and *C. hyperboreus*. Despite the low numerical abundance of Calanoid copepods observed during the fall 2003 survey compared to the previous year, *C. finmarchicus* and *C. hyperboreus* clearly dominate the community in terms of biomass across the entire section. The significance of these changes in copepod body size, community composition and biomass are their effects on the predator-prey dynamics with the higher trophic levels that are dependent on this forage base. Feeding studies of early life stages of pelagic and demersal fish species indicate strong preferences for nauplii and copepodite stages of Calanoid copepods in contrast to strong aversion for nauplii and copepodite stages of Cyclopoid copepods (e.g., *Oithona* sp.), one of the most numerically abundant copepods on the Shelf (Pepin and Penney 1997).

To sum up, the shallow water over the Flemish Cap, combined with the proximity of large-scale oceanic circulation around the Bank including the Labrador Current and the North Atlantic Current, which generate an anticyclonic gyre, elevate water temperatures, and entrain North Atlantic Current waters rich in inorganic nutrients, may provide an advantage to primary and secondary producers in this region compared to the Grand Bank Shelf region.

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Variability of the Labrador Current From Satellite Altimetry

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Sommaire

Des données altimétriques satellitaires de TOPEX/Poseidon (T/P) sont utilisées pour monitorer la variabilité du courant du Labrador le long de la pente continentale de Terre-Neuve pour la période 1992-2002. Les anomalies de courant perpendiculaires aux tracés au sol du satellite sont calculées à partir des pentes de la surface de la mer parallèles au tracés au sol du satellite selon une approximation géostrophique. Les courants de surface absolus sont approximés par la somme des anomalies du courant altimétrique et les courants moyens annuels obtenus d'un model. Le courant du Labrador montre une variabilité intra-saisonnière, saisonnière et interannuelle significative. Près de la queue du Grand Banc, le flux le long des isobathes peut atteindre 70 cm s^{-1} dans le sens de l'équateur, mais montre également de fréquents renversements dans le sens du pôle. Le volume de transport moyen saisonnier entre les isobathes de 200 et 3000 m et entre la surface et 200 m est calculé en utilisant les courants de surface absolus et en assumant un profil de courant invariable sur la profondeur. Ce calcul fournit un indice approximatif de la variation de basse-fréquence du courant du Labrador. À l'échelle saisonnière, le courant du Labrador était plus fort durant la période d'automne/hiver et plus faible durant la période de printemps/été. Pour la période sous étude, le courant du Labrador semble montrer ses plus fortes valeurs en 1996-97.

Introduction

The Labrador Current flows equatorward along the shelf edge and upper continental slope and along the inner shelf off Labrador and Newfoundland, carrying waters of Arctic origin that have unique bio-physical properties. The Labrador Current can significantly affect the physical environment, biological properties, and ocean productivity on the entire Canadian Atlantic Shelf, especially on the interannual scale.

The volume transport associated with the Labrador Current is mainly carried by its shelf-edge branch. The shelf-edge branch northeast of the Grand Bank continues southward through the Flemish Pass and toward the Tail of the Grand Bank (Fig. 1), with some water moving around the Tail of the Bank and along the southwestern Newfoundland Slope and some turning offshore (Petrie and Anderson 1983). An eastward branch north of Flemish Cap has also been identified but is not well studied (Loder et al. 1998).

The variability in the Labrador Current has been investigated using in situ measurements (e.g., Petrie and Anderson 1983) and numerical models (e.g., Hannah et al. 1995). The advent of space-based

Earth observation technology provides an unprecedented opportunity for monitoring ocean variability (e.g., Han and Tang, 1999; Han and Tang, 2001). It is now possible to estimate time series of important indices such as volume, heat, and chlorophyll fluxes, either exclusively based on the satellite observations or in conjunction with in situ measurements and/or model results. Independent in situ data are required to validate the estimated quantities.

In this study, I use T/P satellite altimeter data to investigate variability in the Labrador Current. The objective of this work was to establish a proxy index for monitoring seasonal and interannual variability of the volume transport in the Labrador Current.

Altimetry Data and Methods

I used T/P sea-surface height data for the period from mid 1992 to early 2002 obtained from the NASA Pathfinder Project. The satellite has a nominal repeat cycle of 10 days, so ideally there are 360 observations at each location. There are ascending (southwest to northeast) and descending (northwest to southeast) tracks with spacings of about 200 km in the study region (Fig. 1); the along-track resolution is about 6 km. The data were corrected based primarily on the principles in Benada (1997) for various atmospheric and oceanographic effects.

An along-track Butterworth digital filter with a filter width of 46 km was applied to the sea surface height (SSH) to reduce noise. A time-averaged sea surface was constructed from the T/P data. I then calculated SSH anomalies relative to the mean sea surface. Both the marine geoid and mean oceanic topography are removed by this procedure.

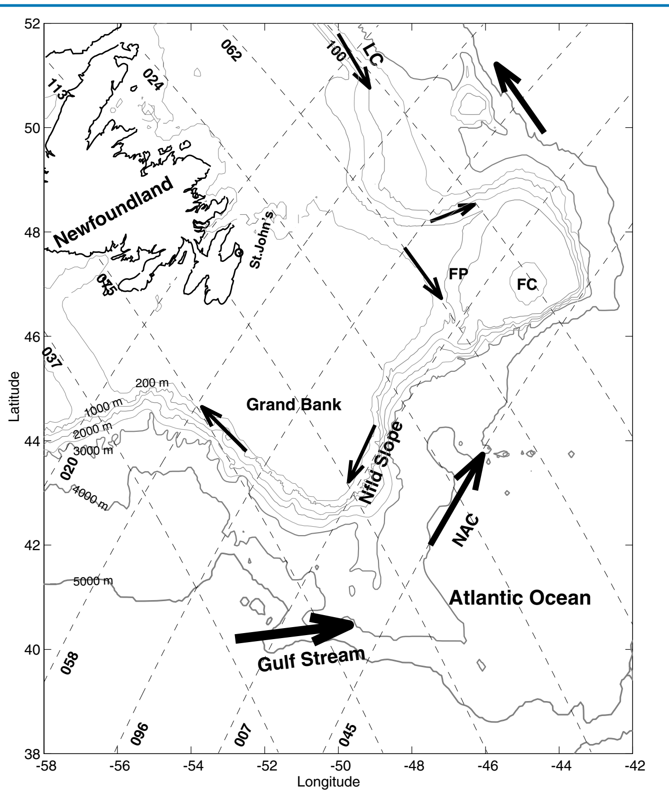

Fig. 1 Map showing the Newfoundland Slope and adjacent shelf and deep oceans. The numbered tracks (dashed lines) are the selected T/P ground tracks that were analyzed. FP: Flemish Pass; FC: Flemish Cap; NAC: North Atlantic Current; LC: Labrador Current.

Carte montrant les régions de la pente et du plateau continental de Terre-Neuve ainsi que les régions profondes adjacentes de l'océan. Les tracés numérotés (traits discontinus) sont les tracés TOPEX/Poseidon qui ont été sélectionnés pour l'analyse. FC: Flemish Cap; FP; Flemish Pass; NAC; North Atlantic Current; LC : Labrador Current.

From the T/P SSH anomalies, geostrophic surface current anomalies perpendicular to the track (positive westward) were derived. The estimated geostrophic current anomalies have a root mean square (RMS) error of ~4 cm s^{-1}. Note that these are estimates of surface current anomalies normal to the satellite ground tracks about the mean only, associated with the along-track pressure gradient anomalies derived from the anomalies of sea surface slope.

An approximate way of constructing absolute surface currents is to combine altimetric surface current anomalies with the mean circulation field from numerical ocean models. In this study, I have used climatological annual mean currents from Han's (2003) model solutions excluding the surface Ekman current. The model produces the Labrador Current transport consistent with observational estimates from moored measurements through the Flemish Pass. A detailed evaluation of the model currents against current meter data has indicated an overall good agreement (with a mean absolute vector difference of 4 cm s^{-1} and a difference ratio [defined as the ratio of the sum of the squared magnitudes of the vector velocity differences to that of the observed velocities] of 0.25) for the primary flow features. Model surface currents were interpolated onto the satellite ground tracks. The components normal to the tracks were then derived and are shown in Figure 2. We can see an equatorward flow along the shelf edge and the upper continental slope.

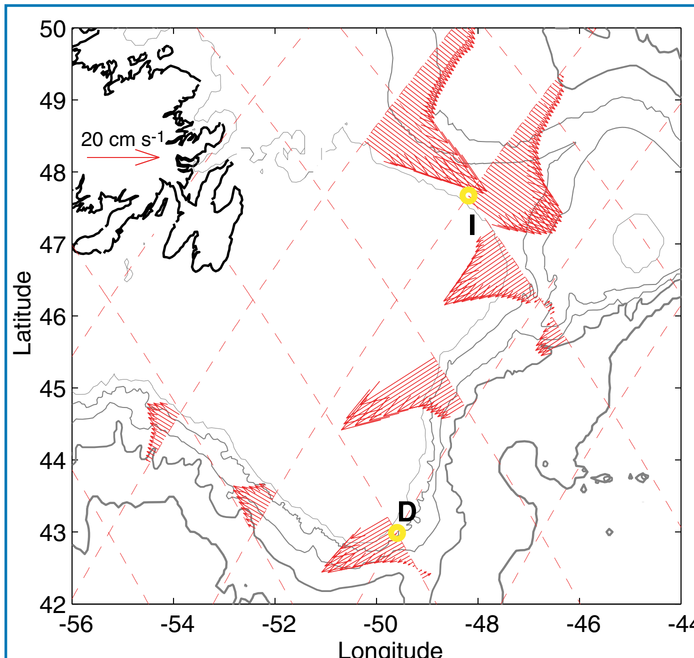

Fig. 2 Climatological annual mean surface currents over the Newfoundland Slope derived from Han's (2003) model results. Only cross-track components are shown. The yellow points I (47.67˚N, 48.19˚W) and D (42.99˚N, 49.60˚W) represent particular crossover points of the satellite tracks.

Climatologie moyenne annuelle des courants de surface au dessus de la pente continentale de Terre-Neuve dérivée des résultats du model de Han (2003). Seulement les composantes transversales aux tracés sont montrées. Les points jaunes I (47.67˚N, 48.19˚O) et D (42.99˚N, 49.60˚O) représentent des points de rencontre particuliers des tracés satellites au sol.

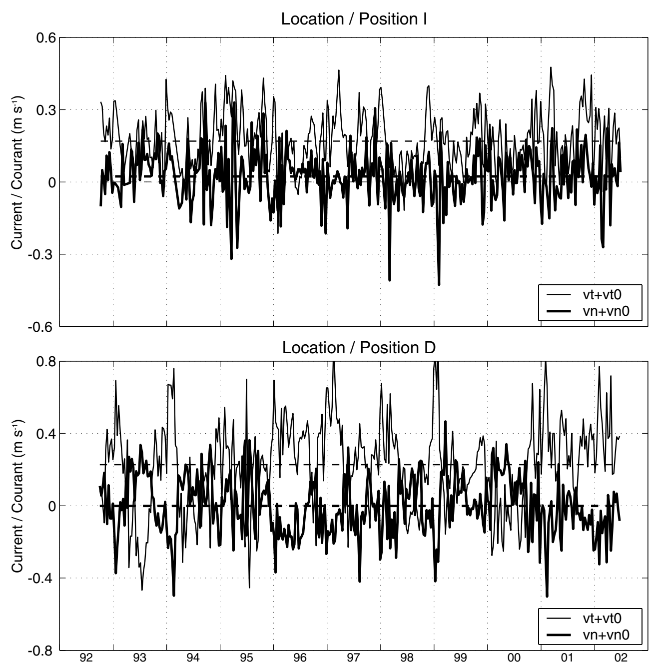

Fig. 3 Time series of along-isobath (thin line) and cross-isobath (thick line) currents at crossovers I and D on the northeast and southeast upper slopes of the Grand Bank, respectively. See Fig. 2 for exact locations. The currents are constructed from TOPEX/Poseidon current anomalies and Han's (2003) annual mean model solutions (dashed lines).

Séries temporelles des courants longitudinaux (ligne mince) et transversaux (ligne épaisse) aux points de brisure I et D respectivement situés sur les pentes supérieures nord-est et sud-est du Grand Banc. Voir Fig. 2 pour leurs positions exactes. Les courants sont construits à partir des anomalies TOPEX/Poseidon et des solutions du model de Han (2003) pour la moyenne annuelle (lignes discontinues).

The crossover points of the descending and ascending tracks are the only locations where we can estimate the total (both directional components) current anomalies from altimetry. I have spatially and temporally interpolated the geostrophic current anomalies normal to descending and ascending tracks to generate time series of the total current anomalies at the crossover points. The normal-to-track components are then transformed into the eastward and northward components as well as the along- and cross-isobath components for further analyses.

Results

There are significant variations at various time scales in the altimetric current anomalies, as seen in the time series of the anomalies (Fig. 3) at crossovers I (water depth of about 200 m) and D (water depth of about 1000 m). Although the annual mean model currents are mainly along the isobath, the altimetric current anomalies clearly indicate significant along- and cross-isobath components. The RMS values of the altimetric current anomalies at I are 11.7 and 10.6 cm s^{-1} in the along- and cross-isobath directions, respectively; those at D are 24.9 and 16.1 cm s^{-1}, respectively. The total along-isobath current at I is directed equatorward almost all the time while that at D features frequent reversals. The maximum equatorward current can reach 70 cm s^{-1} at D and 40 cm s^{-1} at I.

The spatial distribution of the RMS variability of the altimetric cross-track current anomalies (Fig. 4) indicates along-slope variations. Typical values are 10-20 cm s^{-1} over the southwestern (SW) and northeastern (NE) slopes and 20-30 cm s^{-1} over the southeastern (SE) slope. Differences between the upper (200-1000 m) and lower (1000-3000 m) slopes are not significant for the northeastern Newfoundland Slope. There is a suggestion of a weak secondary maximum in RMS currents over the upper slope and a clear indication of a maximum between the upper and lower slope south of Grand Bank, which may reflect variability in the Labrador Current.

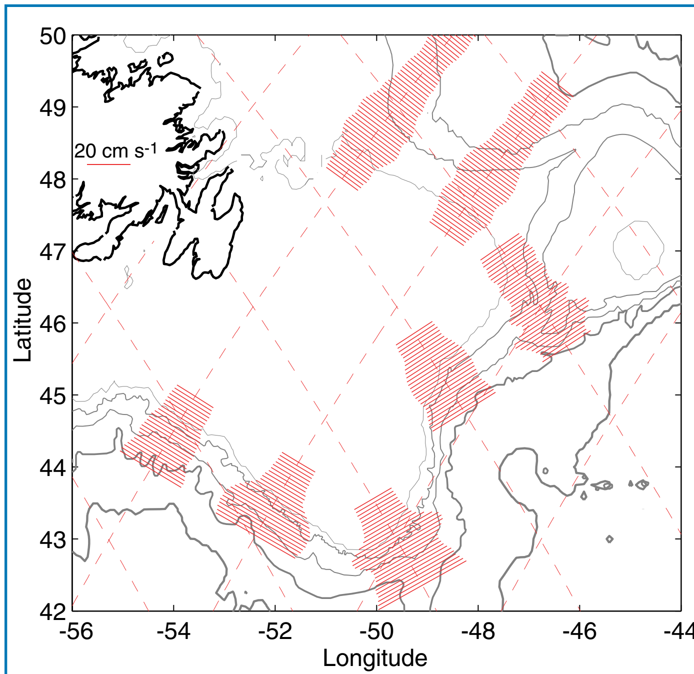

Fig. 4 Variability of the altimetric cross-track current anomalies from 1992 to 2002 plotted as twice the RMS values.

Variabilité des anomalies du courant perpendiculaire aux tracés altimétriques pour la période 19932 à 2002 tracées comme deux fois leurs valeurs RMS (« Root Mean Square »).

Altimetric seasonal mean current anomalies (Jan-Mar, Apr-Jun, Jul-Sep, and Oct-Dec for winter, spring, summer, and fall, respectively)

Table 1 Mean and RMS (Root Mean Square) values (cm s^{-1}) of the seasonal mean T/P surface current anomalies (positive equatorward), Han's (2003) seasonal model current anomalies, and their differences (T/P minus model) over the Newfoundland Slope (between the 200 and 4500 m isobaths). The model current anomalies were calculated by subtracting the annual mean from the four seasonal solutions. The values over the SW, SE, and NE slopes were calculated for tracks 058 and 096, for tracks 113, 024, and 062, and for tracks 096 and 058, respectively.

Moyenne et valeurs RMS (cm s^{-1}) des anomalies saisonnières moyennes des courants T/P (positif vers l'équateur), anomalies saisonnières de courant calculées par le modèle de Han (2003), et leurs différences (T/P moins le model) au dessus de la pente continentale de Terre-neuve (entre les isobathes de 200 et 4500 m). Les anomalies de courant du modèle ont été calculées en soustrayant la moyenne annuelle des quatre solutions saisonnières. Les valeurs au dessus des pentes sud-ouest, sud-est et nord-est sont respectivement calculées pour les tracés 058 et 096, les tracés 113, 024 et 062, et les tracés 096 et 058.

		SW Slope		SE Slope		NE Slope	
		Winter	Summer	Winter	Summer	Winter	Summer
Mean	T/P	6.8	-4.0	3.5	-1.8	1.2	-1.0
	Model	4.8	-5.2	2.9	-4.1	1.6	-0.9
	Difference	2.0	1.2	0.6	2.3	-0.4	-0.1
RMS	T/P	7.2	4.4	5.6	3.6	2.4	1.7
	Model	5.2	6.2	4.0	4.6	2.3	1.5
	Difference	3.2	3.6	3.8	3.9	2.1	1.4

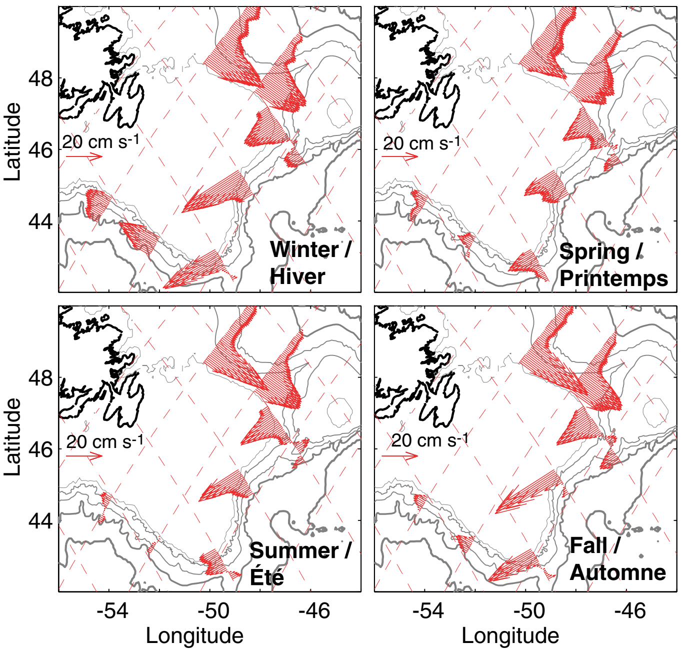

Fig. 5 Seasonal mean surface currents over the Newfoundland Slope in winter, spring, summer and fall (altimetric anomalies plus annual means from Han's [2003] model).

Moyenne saisonnière des courants de surface au dessus de la pente continentale de Terre-Neuve en hiver, au printemps, en été et à l'automne (anomalies altimétriques plus les moyennes annuelles estimées par le modèle de Han 2003).

were calculated from the T/P current anomaly data. Seasonal mean current fields (Fig. 5) were then constructed by adding the annual mean model flows derived from Han (2003) to the altimetric seasonal mean anomalies. Overall, the seasonal variation in the shelf-edge Labrador Current is weak compared with its mean, which is consistent with previous diagnostic model results (Hannah et al. 1995). The equatorward shelf-edge current is stronger in fall/winter and weaker in spring/summer. The seasonal ranges are typically 5-10 cm s-1 and can reach up to 10-20 cm s-1 (e.g., on track 024).

The shelf-edge Labrador Current variability derived from the T/P altimetry is in good qualitative agreement with earlier studies using moored measurements and circulation models (e.g., Petrie and Anderson 1983, Hannah et al. 1995, DeTracey et al. 1996). These observational and model studies have indicated dominant equatorward currents in this region, stronger in fall/winter and weaker in spring/summer.

A detailed comparison of the altimetry-derived cross-track current anomalies with Han's (2003) diagnostic seasonal model solutions also shows good qualitative and approximate quantitative agreement in the seasonality of the shelf-edge Labrador Current (Table 1). Both altimetric and model results indicate mean current anomalies of 2-5 cm s-1 increasing from the NE to SE to SW slope. The equatorward Labrador Current is stronger in winter and weaker in summer. The mean vector differences between the altimetric and model results are substantially smaller than the respective means except on the SE slope in summer. The RMS difference is generally smaller compared with the RMS altimetric or model currents, providing further quantitative evidence of consistency not only in the current magnitude but also in the cross-shelf location and extent.

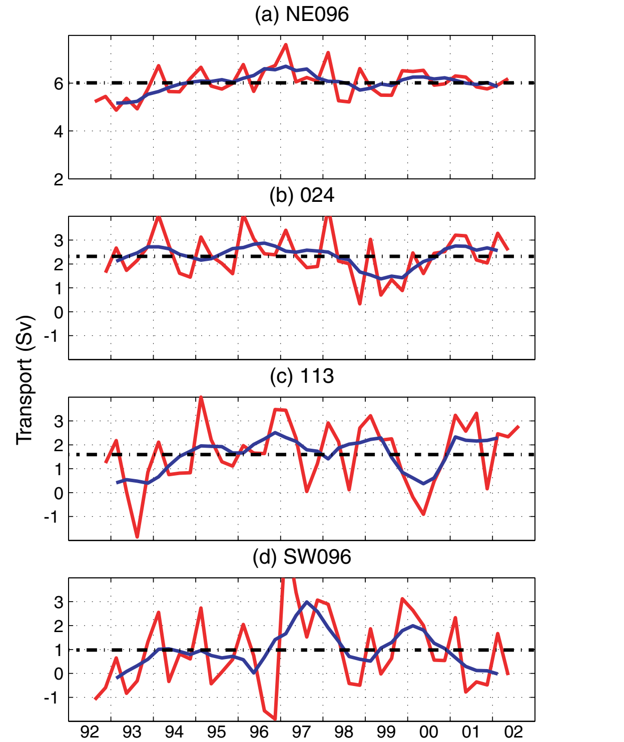

Fig. 6 Volume transport of the Labrador Current (positive equatorward) between the 200 and 3000 m isobaths from altimetric seasonal mean anomalies (red) and Han's (2003) model means (dash-dotted) for (a) NE096 (on the NE Newfoundland Slope), (b) 024, (c) 113, and (d) SW096 (on the SW Newfoundland Slope). The blue line shows the interannual variability after the annual and semi-annual cycles were removed and a five-point moving filter was applied to the altimetric seasonal mean anomalies.

Volume de transport du courant du Labrador (positif vers l'équateur) entre les isobathes de 200 et 3000 m calculé à partir des anomalies saisonnières altimétriques (rouge) et les moyennes (points discontinus) du modèle de Han (2003) pour (a) NE096 (sur la pente nord-est de Terre-Neuve), (b) 024, (c) 113 et (d) SW096 (sur la pente sud-est de Terre-Neuve). La ligne bleu indique la variabilité interannuelle après que les cycles annuels et semi-annuels aient été enlevés et qu'un filtre de cinq points ait été appliqué aux moyennes saisonnières des anomalies altimétriques.

The monthly mean volume transport (1 Sv = 106 m^3 s^{-1}) was calculated using the T/P surface current anomalies and Han's (2003) annual mean surface currents for selected tracks from the 200 to 3000 m isobath and between the sea surface and 200 m in depth. The calculated transport values can nominally represent the strength of the Labrador Current, in spite of limitations such as the assumption of depth-invariable current and the use of only part of the water column. After the annual and semiannual cycles are removed, the monthly means are averaged to obtain seasonal means by season and year, which are then smoothed by a five-point moving filter. There are significant interannual changes (Fig. 6) besides the seasonal fluctuation (Fig. 5) associated with the Labrador Current over the Newfoundland Slope. The Labrador Current appeared to be intensified on the NE and SE Newfoundland Slope in 1996/97 and on the SW Newfoundland Slope in 1997. The intensification is consistent with moored measurements of a stronger and colder westward shelf-edge current off St. Pierre Bank in 1997 (P.C. Smith, BIO, DFO, personal communication, 2000) and Han's (2002) suggestion of a Labrador Current pulse traveling through the Scotian Slope in 1997/1998.

Summary

I used TOPEX/Poseidon (T/P) altimeter data from 1992 to 2002 to investigate the Labrador Current variability over the Newfoundland Slope. Cross-track geostrophic surface current anomalies were derived from along-track sea surface slopes. Absolute surface currents were approximated by the sum of altimetric current anomalies and annual mean model currents.The T/P results revealed strong variability at various temporal and spatial scales. Near the Tail of the Grand Bank, the along-isobath flow can reach 70 cm s^{-1} equatorward but features frequent reversals (poleward).Typical RMS variability of the cross-track current anomalies is 10-20 cm s^{-1} over the SW and NE slopes and 20-30 cm s^{-1} over the SE Slope.The transport index calculated between the 200 to 3000 m isobaths and for the top 200 m was stronger in fall and weaker in spring.The seasonal range amounts to 10-20 cm s^{-1}. On the interannual scale, the Labrador Current seemed to be strongest in 1996-97.The study demonstrates the ability of satellite altimetry to monitor the seasonal and interannual variability of the Labrador Current.The present work is being expanded to include heat and chlorophyll indices of the Labrador Current by combining satellite altimetry with satellite-derived sea-surface temperature and ocean colour.

Acknowledgements

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Utilisation de la télédétection spatiale pour distinguer les diatomées dans une population phytoplanctonique en milieu océanique

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Abstract

Different species of phytoplankton bloom during different periods of the year in the northwest Atlantic. Diatoms in particular are responsible for strong spring blooms on the continental shelf off Nova Scotia. These blooms then move toward the north. Many studies have shown that the optical absorption properties of diatoms are different from those of other phytoplankton populations and that these differences in the absorption characteristics of the oceanic environment can induce a bias in the estimation of chlorophyll *a* as measured by spaceborne remote sensing. These differences in optical properties have been exploited to allow the spaceborn remote sensing identification of diatom populations in the marine environment. In this paper we present the algorithm that was developed and applied to the SeaWiFS data and we show how the results obtained compare with data from in situ HPLC analyses performed on samples taken during missions of the Atlantic Zone Monitoring Program.

Introduction

La multiplication des capteurs satellitaires de la couleur de l'eau permet l'observation des océans d'une manière globale et quotidienne. Actuellement, la NASA fournit à la communauté scientifique les données du capteur SeaWiFS ainsi qu'un logiciel de traitement et d'interprétation des données (SeaDAS). Après avoir effectué les corrections atmosphériques afin d'obtenir les luminances marines ascendantes, l'algorithme OC4 de la NASA (O'Reilly et al. 1998) permet d'estimer les concentrations en chlorophylle *a* et de produire des cartes de répartition à l'échelle globale des océans. La chlorophylle *a* peut alors être utilisée pour estimer la production primaire qui peut ensuite être inclue dans des modèles biogéochimiques du cycle du carbone, ou encore être utilisée à des fins de prévision pour les pêches. Toutefois, il a été démontré que l'algorithme OC4 de la NASA a des performances limitées lorsqu'il est appliqué à une échelle locale (Reynolds et al. 2001, Gohin et al. 2002, Sathyendranath et al. 2004) et dans ce cas précis, un algorithme régional lui sera préféré.

Un tel algorithme régional, basé sur la théorie du transfert radiatif, a été développé à l'institut océanographique de Bedford (Sathyendranath et Platt 1997, 1998). Cet algorithme est particulièrement adapté à la partie nord-ouest de l'océan Atlantique car il utilise les propriétés bio-optiques des populations de phytoplancton que l'on retrouve dans cette région échantillonnée depuis plusieurs années lors des campagnes de mesures du Programme de Monitorage de la Zone Atlantique (PMZA). Plusieurs travaux ont montré que les coefficients d'absorption spécifique du phytoplancton (coefficient d'absorption normalisé à la concentration en chlorophylle) varient avec la taille des cellules (effet d'enveloppe), mais aussi avec leur composition en pigments accessoires (Hoepffner and Sathyendranath 1991, Fujiki et Tagushi 2002, Lohrenz et al. 2003). Ainsi, les cellules de plus grandes tailles ont une absorption spécifique inférieure aux cellules de plus petites tailles. Les diatomées ont, en général, une taille supérieure à 20 µm et sont donc répertoriées comme cellules de grandes tailles. Ce groupe de cellules phytoplanctoniques peut également être identifié grâce à son contenu en pigments auxiliaires puisque qu'il est le seul à contenir le pigment fucoxanthine en quantité suffisante pour en permettre la mesure par chromatographie haute performance en phase liquide (CHPL). Ces caractéristiques ont été utilisées pour développer un algorithme d'identification des diatomées. Celui-ce a été appliqué aux données SeaWiFS et les résultats obtenus ont été comparés avec succès avec des mesures in situ.

Matériel et méthode

À une profondeur et une longueur d'onde donnée, la réflectance se définie comme suit :

$$R(\lambda, z) = \frac{E_u(\lambda, z)}{E_d(\lambda, z)}$$

où $R(\lambda,z)$ représente la réflectance à la longueur d'onde λ et la profondeur z, et E_u et E_d représentent respectivement les éclairements ascendants et descendant aux mêmes longueur d'onde et profondeur. Sathyendranath et Platt (1997, 1998) ont développé un modèle pour exprimer la réflectance ascendante au niveau de la surface de l'eau. Ce modèle, modifié par la suite par Sathyendranath et al. (2001), relie la réflectance à la surface de l'eau aux propriétés optiques d'absorption et rétrodiffusion des composantes océaniques (eau de mer pure, phytoplancton et produits dégradés associés). Il se défini comme suit :

$$R(\lambda) = r\frac{b_b(\lambda)}{a(\lambda) + b_b(\lambda)}$$

où $R(\lambda)$ représente la réflectance à la longueur d'onde λ, $a(\lambda)$ et $b_b(\lambda)$ représentent respectivement l'absorption et la rétrodiffusion à la longueur d'onde λ, et r est un facteur de proportionnalité. Pour une concentration donnée en phytoplancton, la réflectance océanique est calculée aux longueurs d'onde du capteur SeaWiFS dans la partie visible du spectre soit à 412, 443, 490, 510, 555 et 670 nm. Des tables de correspondance ont été crées pour chacune des concentrations en phytoplancton variant entre 0.01 et 40 mg m^{-3} ainsi que pour les réflectances associées.

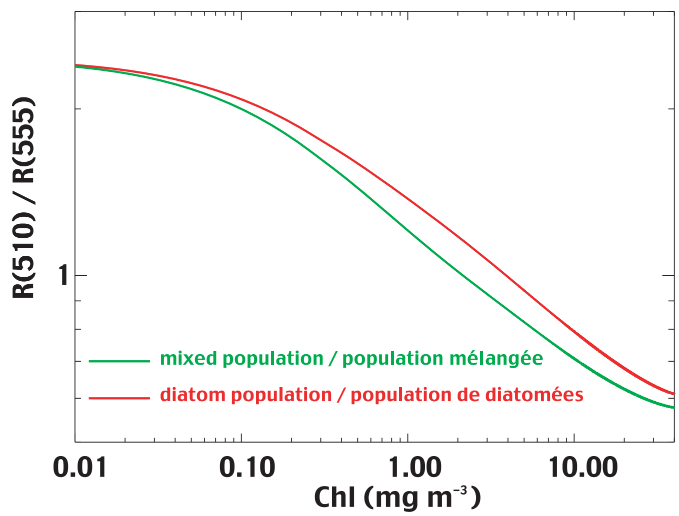

Fig. 1 Rapport de réflectance 510:555 en fonction de la concentration en chlorophylle *a* pour les populations de diatomées ou les populations mélangées.

Reflectance ratio 510:555 as a function of chlorophyll a *concentration for diatom and mixed populations.*

L'absorption du phytoplancton varie d'une manière non uniforme avec la concentration en phytoplancton. Le model utilisé pour modéliser l'absorption est celui de Sathyendranath et al. (2001). Pour cette étude, 222 échantillons ont été prélevés dans le nord-ouest de l'Atlantique durant les campagnes de mesures du PMZA entre 1996 et 1998 pour le développement du modèle, et entre 1999 et 2000 pour sa validation. Les échantillons furent analysés par CPHL et séparés en deux groupes selon leur composition pigmentaire soit un groupe dominé par des populations de diatomées et un autre groupe dominé par des populations mélangées. Les valeurs pour les propriétés optiques des autres composantes océaniques, principalement l'eau de mer et la rétrodiffusion du phytoplancton, proviennent de la littérature.

Le modèle d'absorption fut appliqué à chacun des deux groupes et les résultats furent inclus dans le modèle de réflectance pour ainsi créer deux tables de correspondance reliant la concentration du phytoplancton à la réflectance océanique ascendante aux longueurs d'onde mentionnées plus haut. Plusieurs rapports de réflectance océanique furent examinés afin d'optimiser la relation entre la concentration en phytoplancton et les rapports de réflectance. Il est apparu que les courtes longueurs d'ondes (412 et 443 nm) n'étaient pas exploitables dû à l'impossibilité d'effectuer des corrections atmosphériques lors du calcul du signal océanique à partir du signal au sommet de l'atmosphère. Finalement, les rapports de réflectance sélectionnés furent 510/555 et 490/670. La figure 1 illustre les variations de la réflectance avec la concentration en chlorophylle *a* pour chacun des deux groupes.

L'application aux images satellitaires s'est effectuée pixel par pixel. Pour chaque pixel d'une image, la concentration en chlorophylle *a* est calculée à partir de chaque table de correspondance (510/555 et 490/670) et chaque groupe (populations de diatomées et populations mélangées). Ensuite, pour chacun des groupes, la différence, e, entre les deux concentrations en chlorophylle *a* obtenue en utilisant les deux tables de correspondance est calculée. On retient alors le groupe qui obtient la plus petite différence (le plus petit e) correspondant au modèle adapté. Cette procédure fut répétée pour chaque image de la première quinzaine des mois d'avril et d'août 2000, et des images composites furent construites.

Des mesures in situ correspondant aux images satellites (lieu et date) furent utilisées pour valider le modèle. Un total de 44 stations fut trouvé pour les années 1998, 1999 et 2000. Pour chacune des ces stations, les mesures CHPL furent utilisées pour déterminer la composition pigmentaire des échantillons recueillis, la présence de fucoxantine permettant alors d'identifier les échantillons dominés par des populations de diatomées.

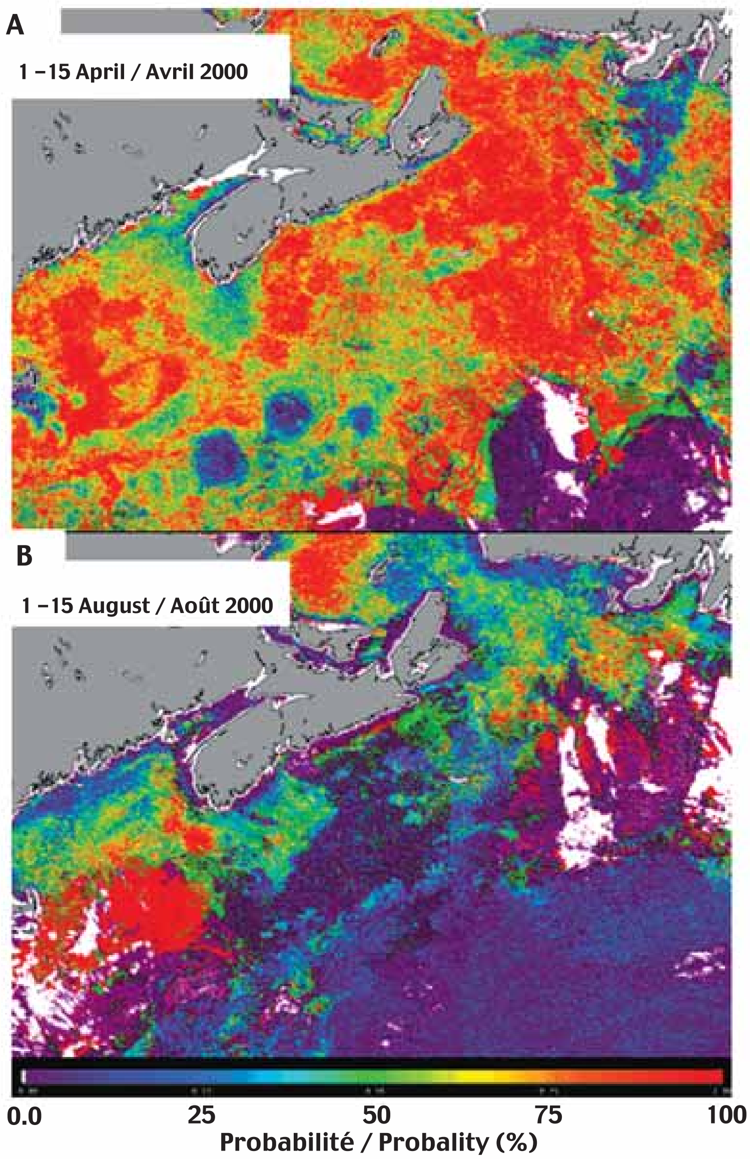

Fig. 2 Probabilité de la présence de diatomées dans la zone d'étude pour les mois (A) d'avril 2000 et (B) d'août 2000.

Probability of occurrence of diatom blooms in the study area for (A) April 2000 and (B) August 2000.

ponctuelle avec un pixel de résolution spatiale de 1 km^2.

Il semble donc possible d'examiner l'évolution spatiale (horizontale) des floraisons de diatomées au cours de l'année en utilisant la télédétection. Les images satellitaires de la zone nord-ouest de l'Atlantique illustrent bien d'ailleurs la dominance des diatomées tôt dans l'année (1-15 avril 2000) en comparaison avec le milieu de l'été (1-15 août 2000) (Fig.2). La présence de diatomées sur le banc Georges aux deux différentes périodes de l'année est également en accord avec les observations déjà rapportées dans la littérature (Hoeppfner et Sathyendranath 1992, 1993).

L'identification des populations de diatomées permet aussi l'utilisation de l'algorithme adéquat lors du calcul de la concentration en chlorophylle *a* (Fig. 3). L'utilisation de l'algorithme OC4 de la NASA fournit une erreur quadratique moyenne de 51 % alors que l'utilisation de notre modèle semi-analytique avec identification de populations de diatomées fournit une erreur quadratique moyenne de 31 %. La figure 4 illustre les concentrations en chlorophylle *a* dans la région d'étude, calculées en utilisant l'algorithme « discriminatoire ». Celui-ci présente l'avantage de tenir compte des caractéristiques optiques saisonnières et régionales des propriétés optiques des constituants océaniques. En outre, il permet d'éviter des discontinuités dans l'image telle que celles observées lorsque des algorithmes « sélectifs » sont choisis.

Résultats et discussion

Lorsque l'on compare la classification des échantillons CHPL avec la classification obtenue en utilisant l'algorithme couplé aux données satellitaires pour la période du début avril 2000, on obtient une correspondance de 72 % pour l'identification des échantillons dominées par les populations de diatomées, et de 70 % pour les populations mélangées. Durant les deux premières semaines du mois d'août, l'analyse des données CHPL fournit seulement des populations mélangées (9 échantillons), ce qui est cohérent avec l'identification satellitaire puisque le succès des comparaisons atteint 89 %. Il est intéressant de remarquer que seules les données en absorption de 1996 à 1998 furent utilisées pour développer le modèle de réflectance et qu'aucune dégradation n'est observée lorsque l'on applique ce modèle de réflectance à des données satellitaires de l'année 2000. Ces résultats sont très encourageants compte tenu que l'on compare ici une mesure in situ

Conclusion

L'utilisation d'algorithmes « intelligents » permettant d'identifier des populations de phytoplancton représente un grand pas dans l'interprétation des données couleur de l'eau, notamment en permettant une meilleure quantification de la biomasse phytoplanctonique. L'amélioration de la prochaine génération de capteurs de la couleur de l'eau (réduction rapport bruit/signal, meilleure résolution spatiale, augmentation

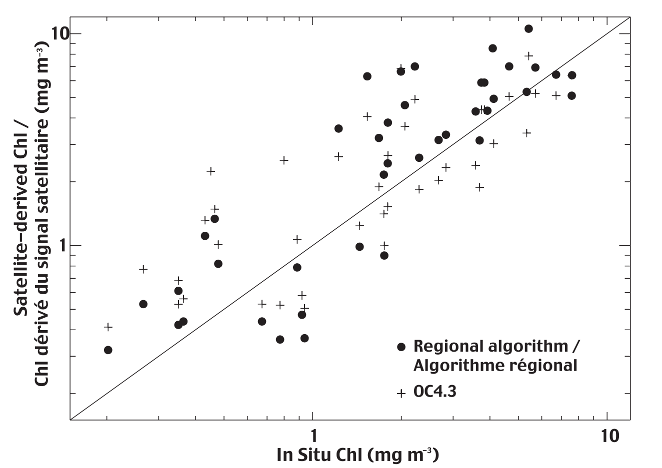

Fig. 3 Comparaison entre la concentration en chlorophylle *a* mesurée par satellite et la concentration en chlorophylle *a* mesurée in situ en utilisant l'algorithme OC4 (+) et l'algorithme régional (•).

Comparison between satellite-derived chlorophyll a *concentrations and in situ chlorophyll* a *concentrations using the OC4 algorithm (+) and the regional algorithm (•).*

du nombre de canaux d'observation) est le présage d'un avenir important pour ce nouveau type d'algorithmes. L'élaboration d'algorithmes permettant la discrimination des populations de diatomées a été rendue possible grâce aux connaissances acquises depuis plusieurs années dans la région du nord-ouest de l'Atlantique et ce, grâce aux mesures in situ effectuées dans le cadre du PMZA. De tels outils sont possiblement exportables à d'autres régions du globe pourvu que les caractéristiques bio-optiques de ces régions aient été définies rigoureusement.

Remerciements

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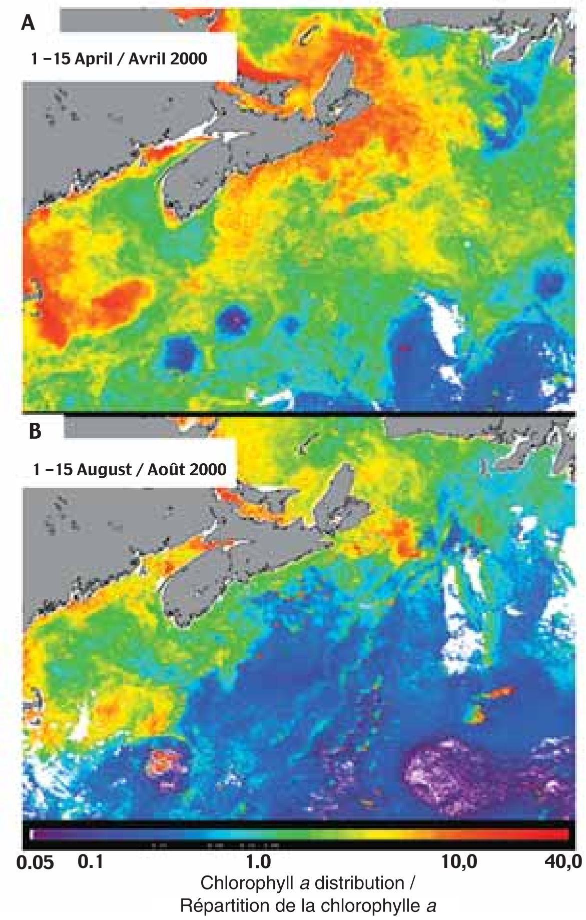

Fig. 4 Images composites de la concentration en chlorophylle *a* dans la zone d'étude, calculées en utilisant l'algorithme régional pour les mois (A) d'avril et (B) d'août 2000.

Composite images of chlorophyll a *concentrations in the study area computed using the regional algorithm for (A) April and (B) August 2000.*

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